Experimental and Numerical Studies of the Temperature Field in Selective Laser Sintering to Improve Shrinkage and Warpage Prediction

Advanced Qualification of Additive Manufacturing Materials Workshop,
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Overview

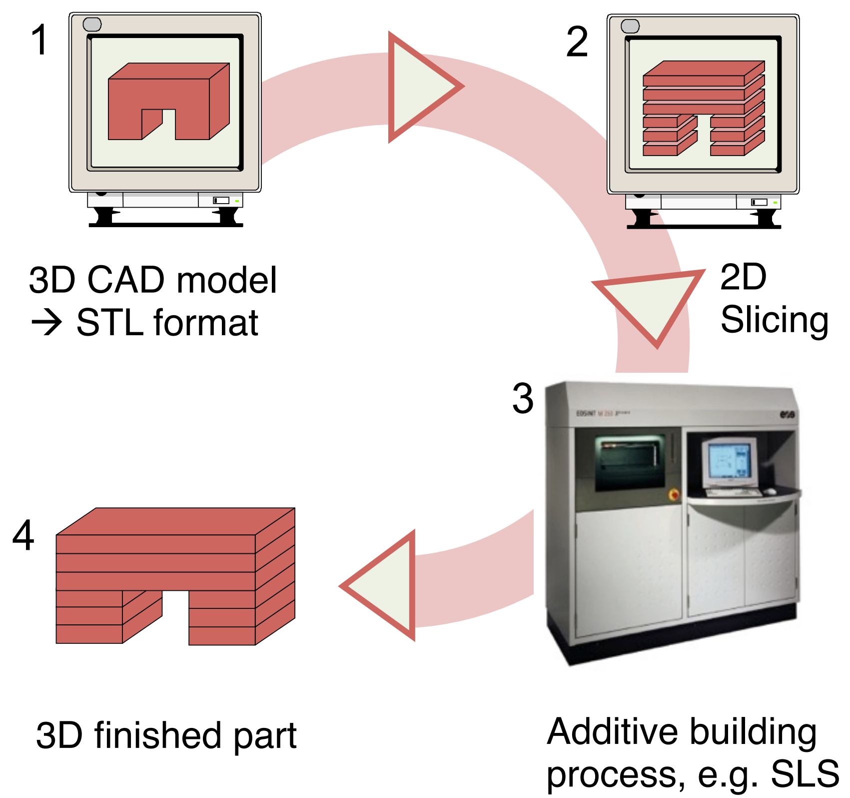
Additive Manufacturing: SLS, FDM®, AFP

- Process characteristics
- Shrinkage and warpage effects

Investigations of impact factors:

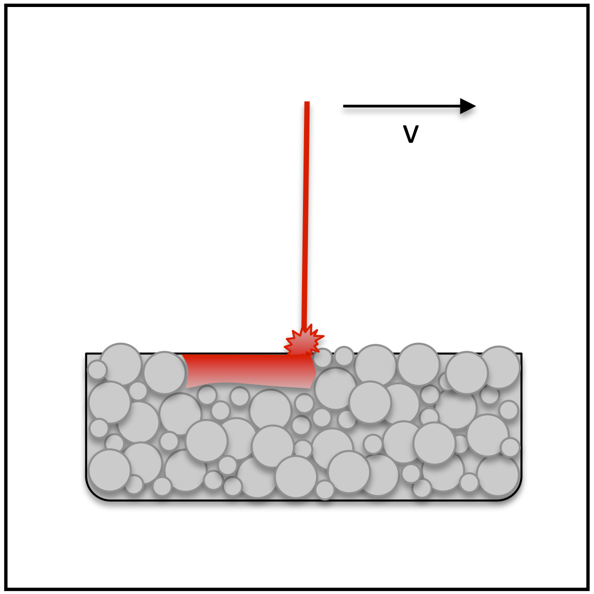
- Study of crystallization
- Study of stiffness development during cooling
- Measurement of temperature field e.g. during coating

Outlook: Online-monitoring of crystallization



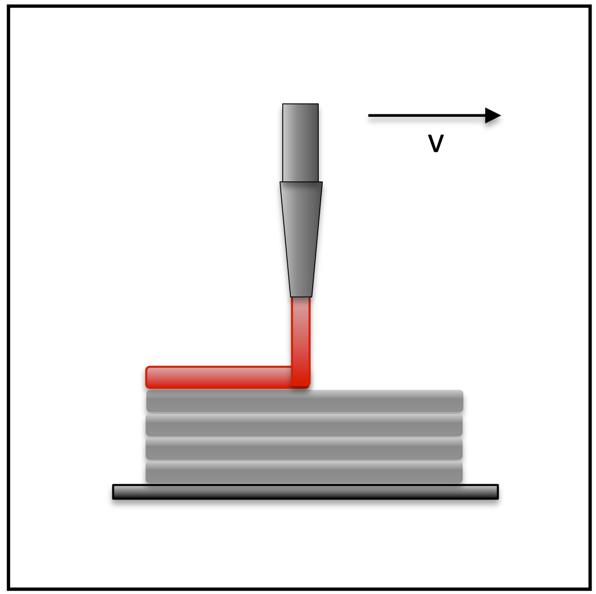
Additive Building Principles

Powder bed fusion: SLS



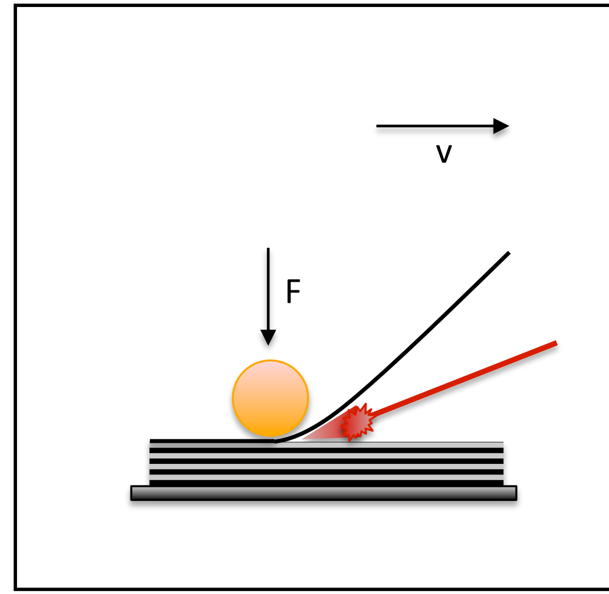
an AM process in which thermal energy selectively fuses regions of a powder bed: **Selective Laser Sintering**

Material extrusion: FDM



an AM process in which material is selectively dispensed through a nozzle or orifice: **Fused Deposition Modeling**

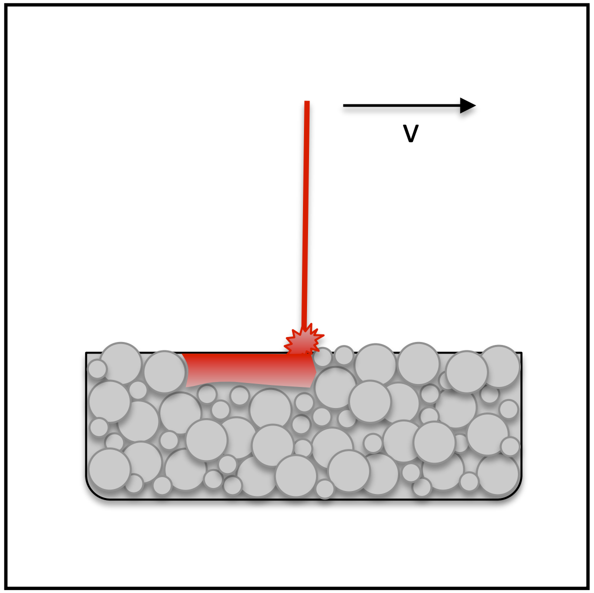
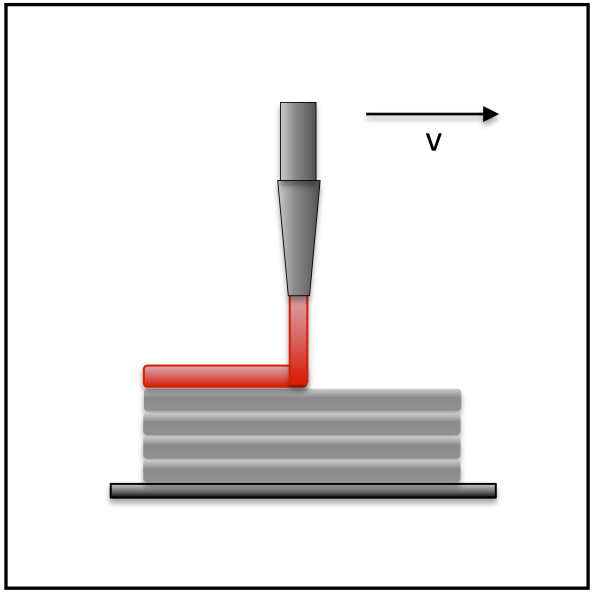
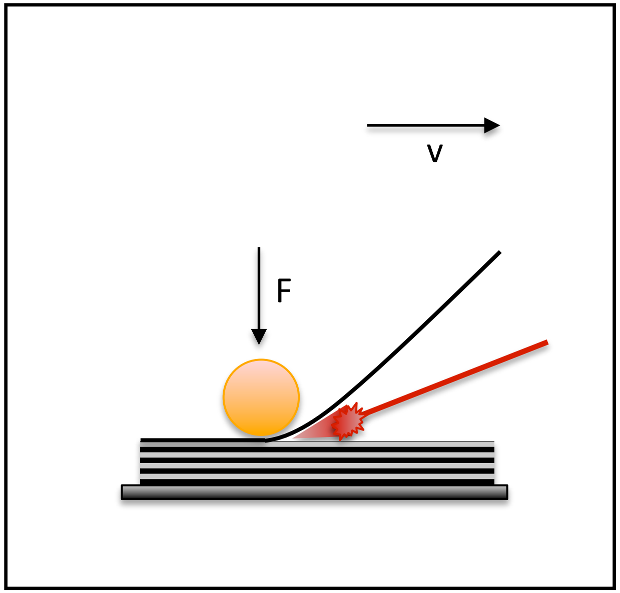
Directed energy depos.: AFP



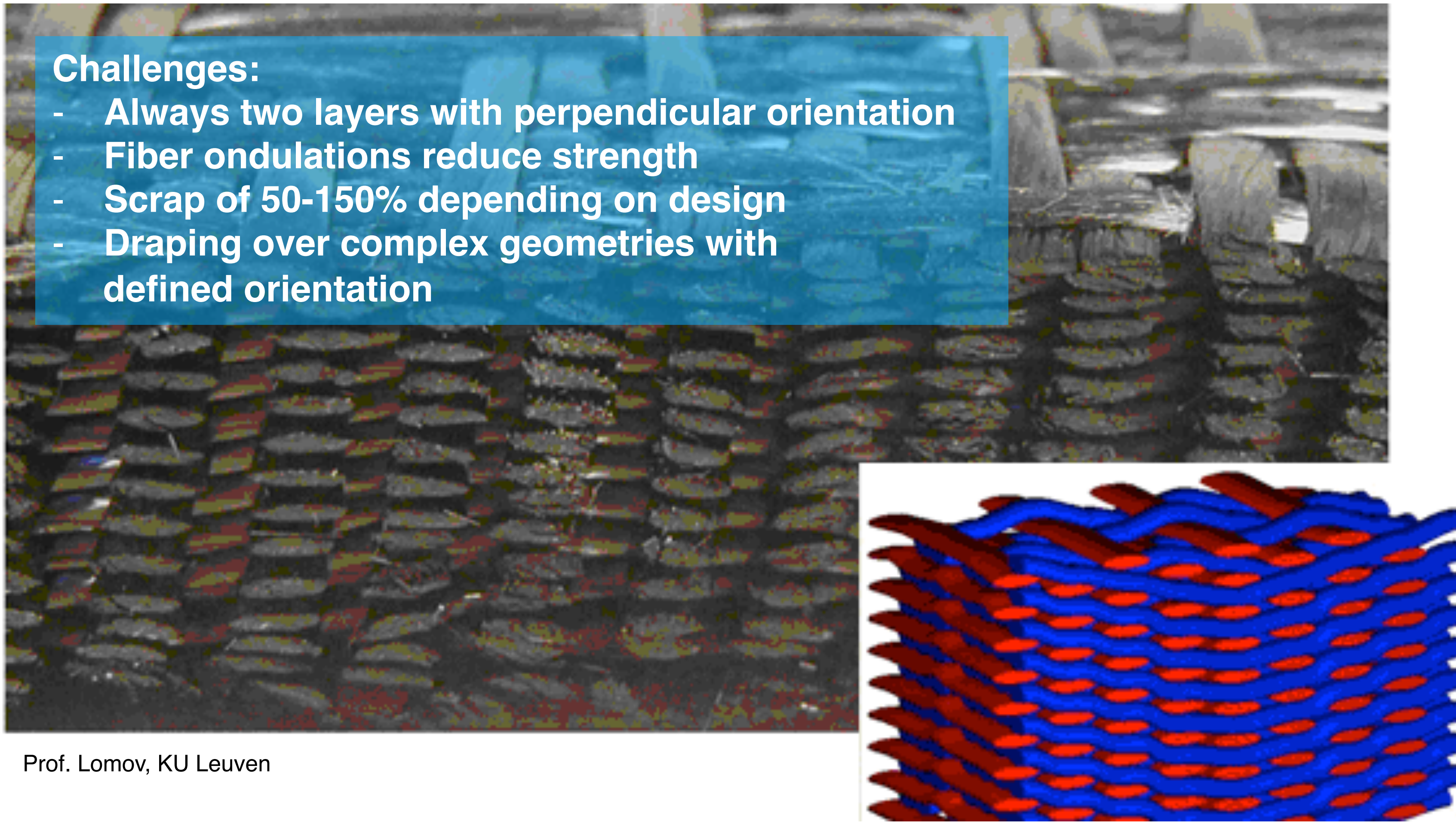
an AM process in which focused thermal energy is used to fuse materials by melting as they are being deposited: **Automated Fiber Placement**

ASTM F2792, 2014

Differences

Powder bed fusion: SLS	Material extrusion: FDM	Directed energy depos.: AFP
		
❑ Local melting of deposited powder ❑ Laser heat source ❑ Surrounding solid powder creates “mold” ❑ Complex 3D shapes	❑ Heat conduction in the nozzle ❑ Deposition of molten material and local remelting ❑ Support material needed ❑ 3D shapes	❑ Local melting of continuous fiber reinforced polymer during deposition ❑ (mostly) laser heat source ❑ Material itself keeps part shape ❑ mostly 2D, curved shapes

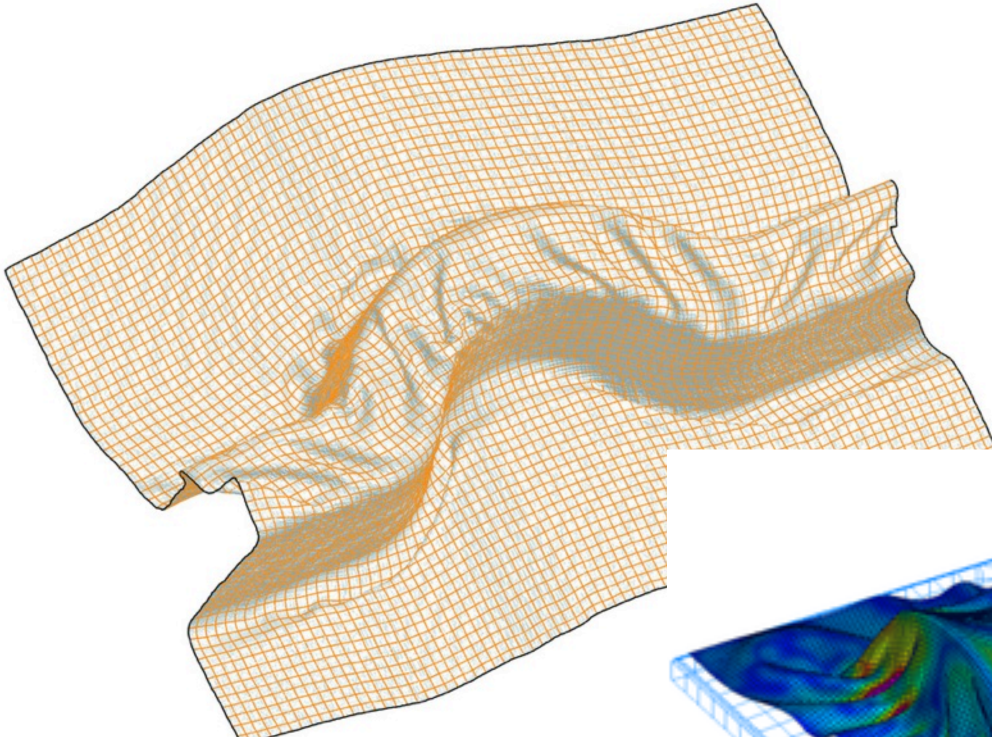
Fiber-Reinforced (Textile) Composites



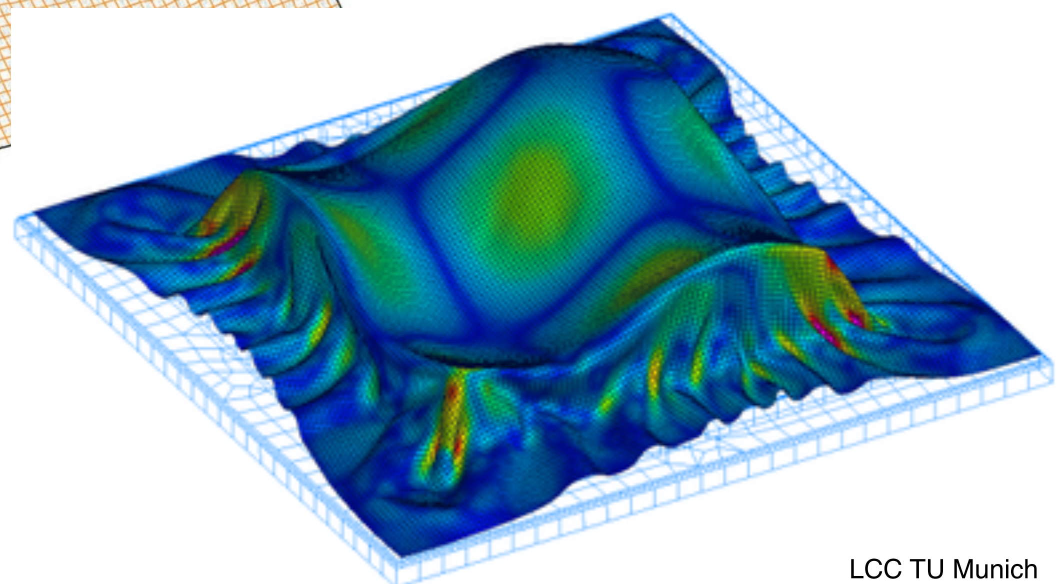
Challenges:
- Always two layers with perpendicular orientation
- Fiber ondulations reduce strength
- Scrap of 50-150% depending on design
- Draping over complex geometries with defined orientation

Prof. Lomov, KU Leuven

Draping of Textiles

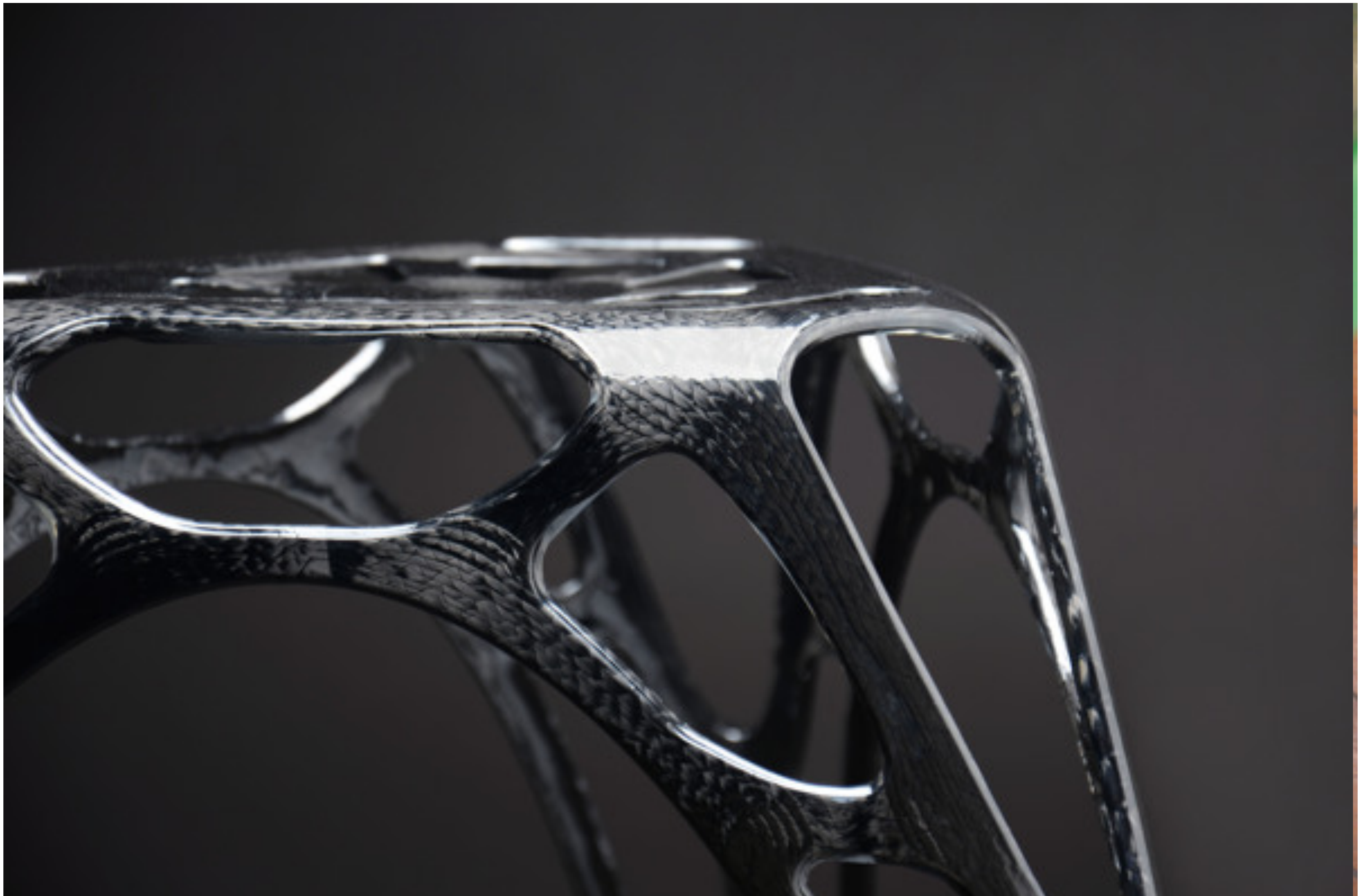


IVW Kaiserslautern

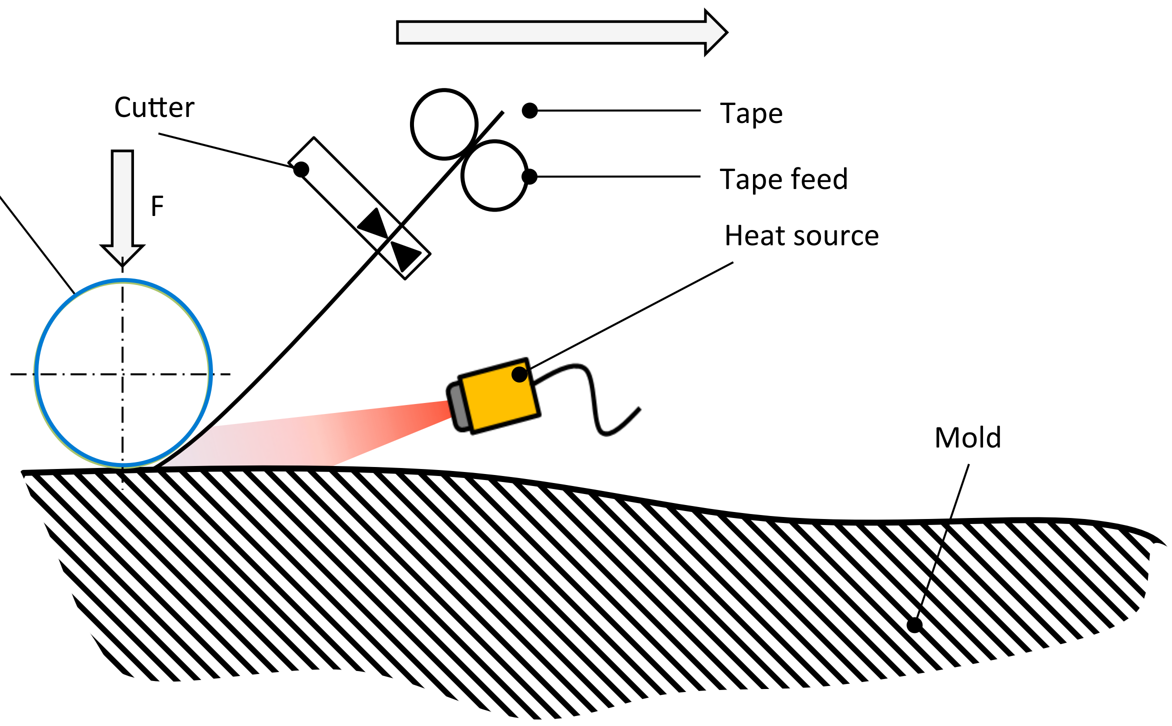


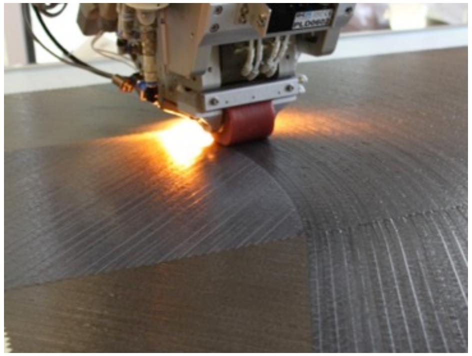
LCC TU Munich

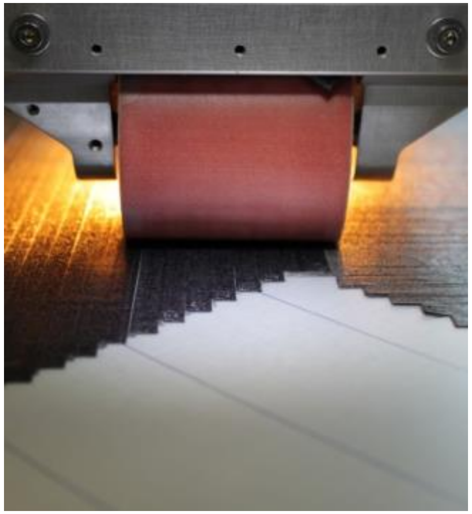
Tailored Fiber Placement



Automated Fiber Placement



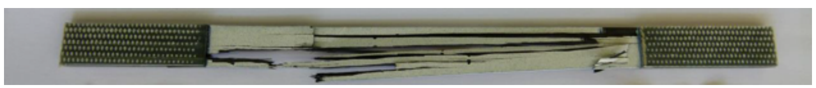


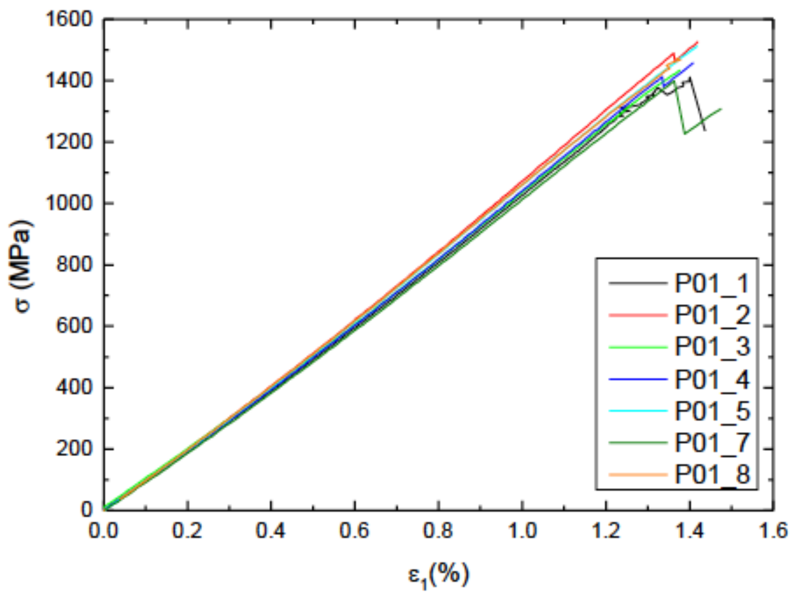


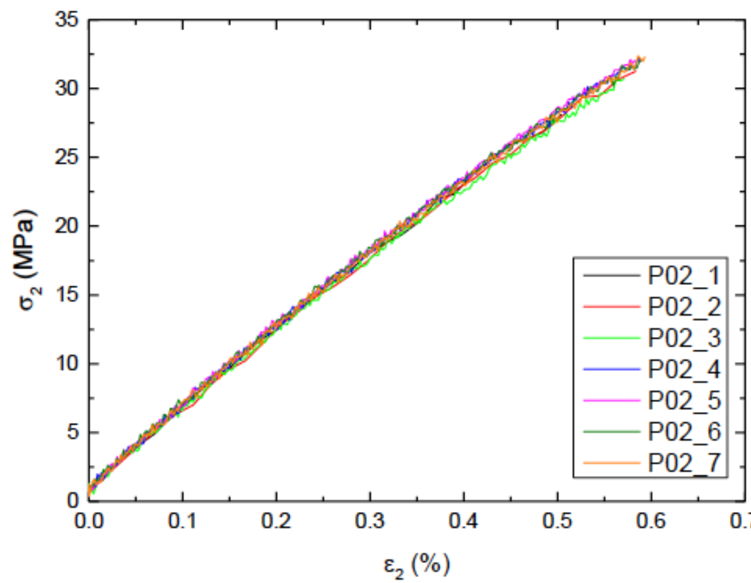
Tensile tests 0° - 90° (PA6 CF)

$0^{º}\ [0]_5$				
	σ_M (MPa)	ε_M (%)	E (GPa)	µ (-)
Mean value	1459.05	1.39	97.75	0.36
Standard dev.	48.68	0.02	2.33	0.01

$90^{º}\ [0]_{10}$			
	σ_M (MPa)	ε_M (%)	E (GPa)
Mean value	31.28	0.57	5.72
Standard dev.	1.52	0.03	0.04

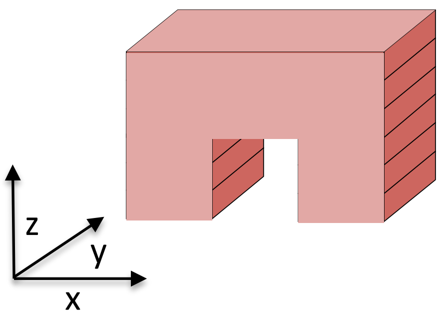


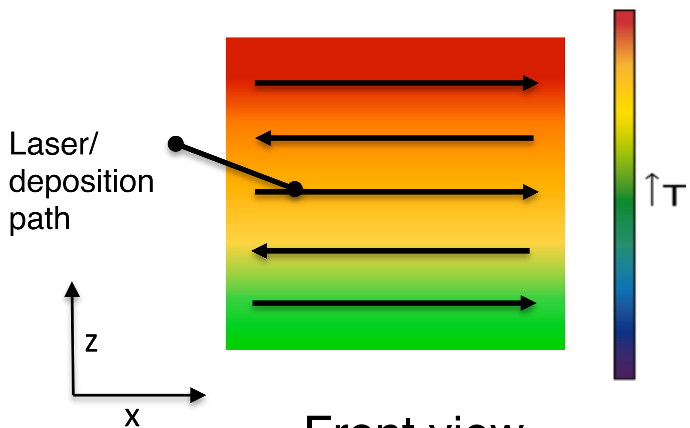




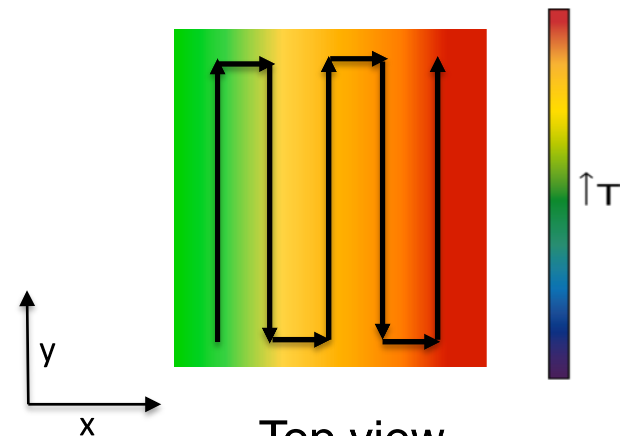
ISO 527-5, 2010

Temperature Distribution during Building

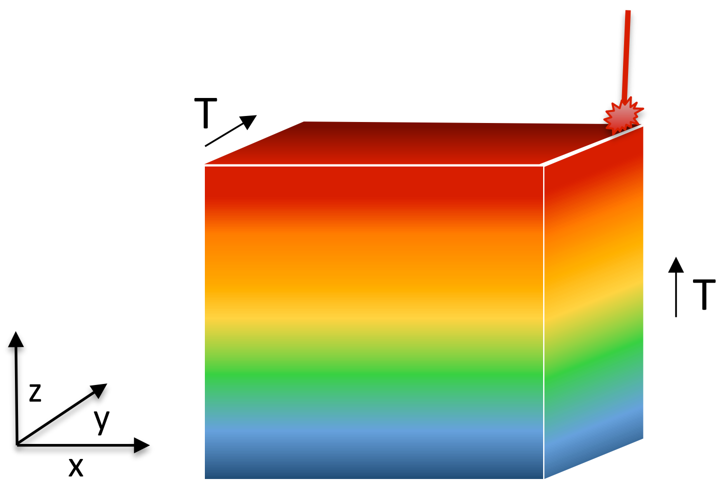




Front view



Top view



The scale/temperature range depends on the process!

Shrinkage and Warpage

- Shrinkage is the difference between the part dimensions in the molten and the solid state due to the volume contraction during cooling
- Residual stresses are formed during cooling due to rapid quenching and shrinkage inhibition
- Warpage is the change of the part shape (e.g. spring-in at corners) due to non-symmetric residual stress distributions. It is caused by:
  - Inhomogeneous shrinkage over the part cross-section (e.g. due to differences in temperature on the part surface)
  - Local shrinkage differences within the part (e.g. due to varying wall thicknesses)
  - Anisotropy of shrinkage (e.g. due to the orientation of molecules or fibers)

$$\sigma = -\frac{2}{3}\frac{E\beta}{1-\upsilon}(T_s - T_f)\cdot \mathbb{R}$$

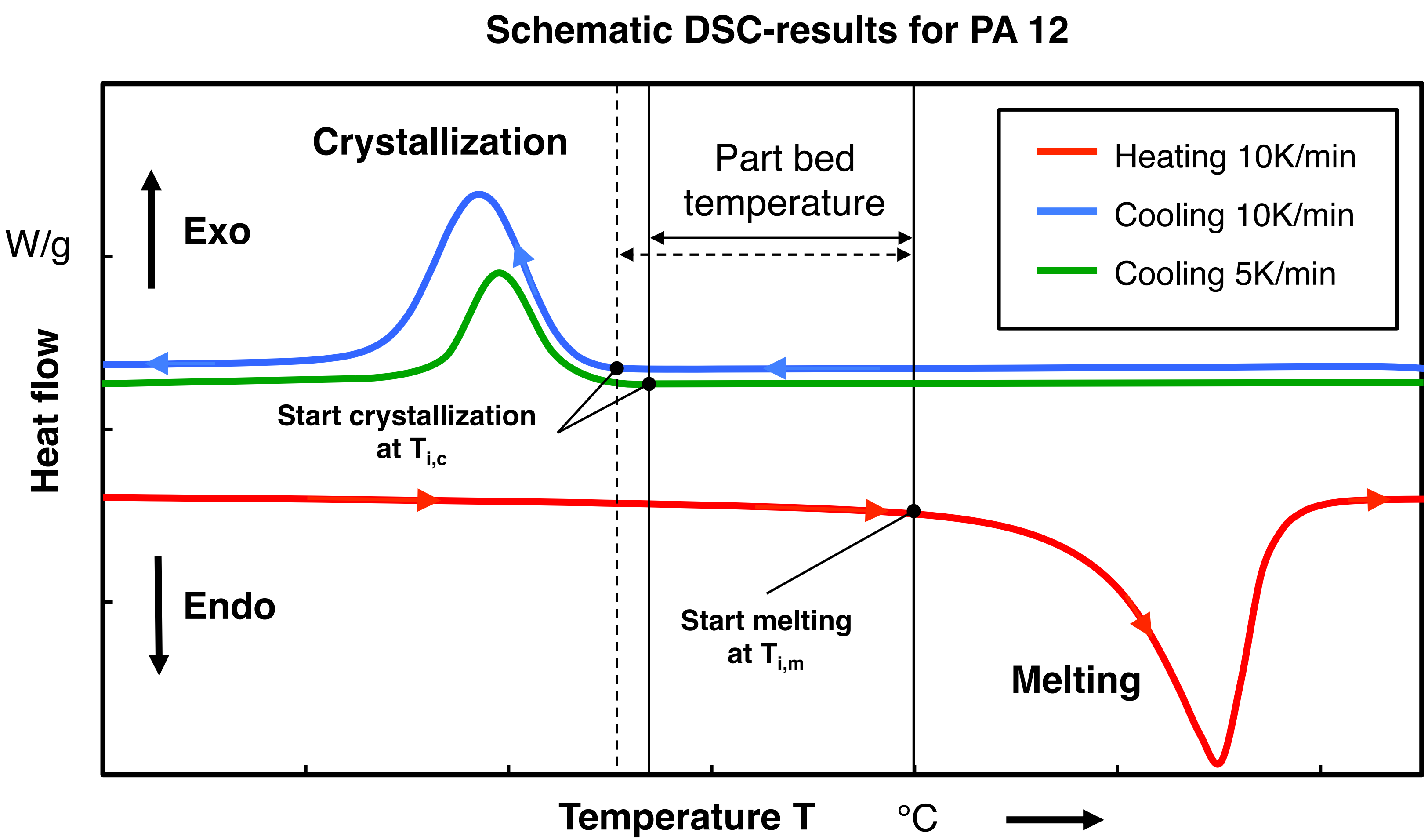
σ= residual stress, E= Young's modulus, b= thermal expansion coefficent, v= Poisson's ratio, T_s, T_f= solidification and final temperature, $\mathbb{R}$ = geometric factor

Residual stress model without phase change effects (derived from dimensional analysis)

Osswald/Menges, 2012

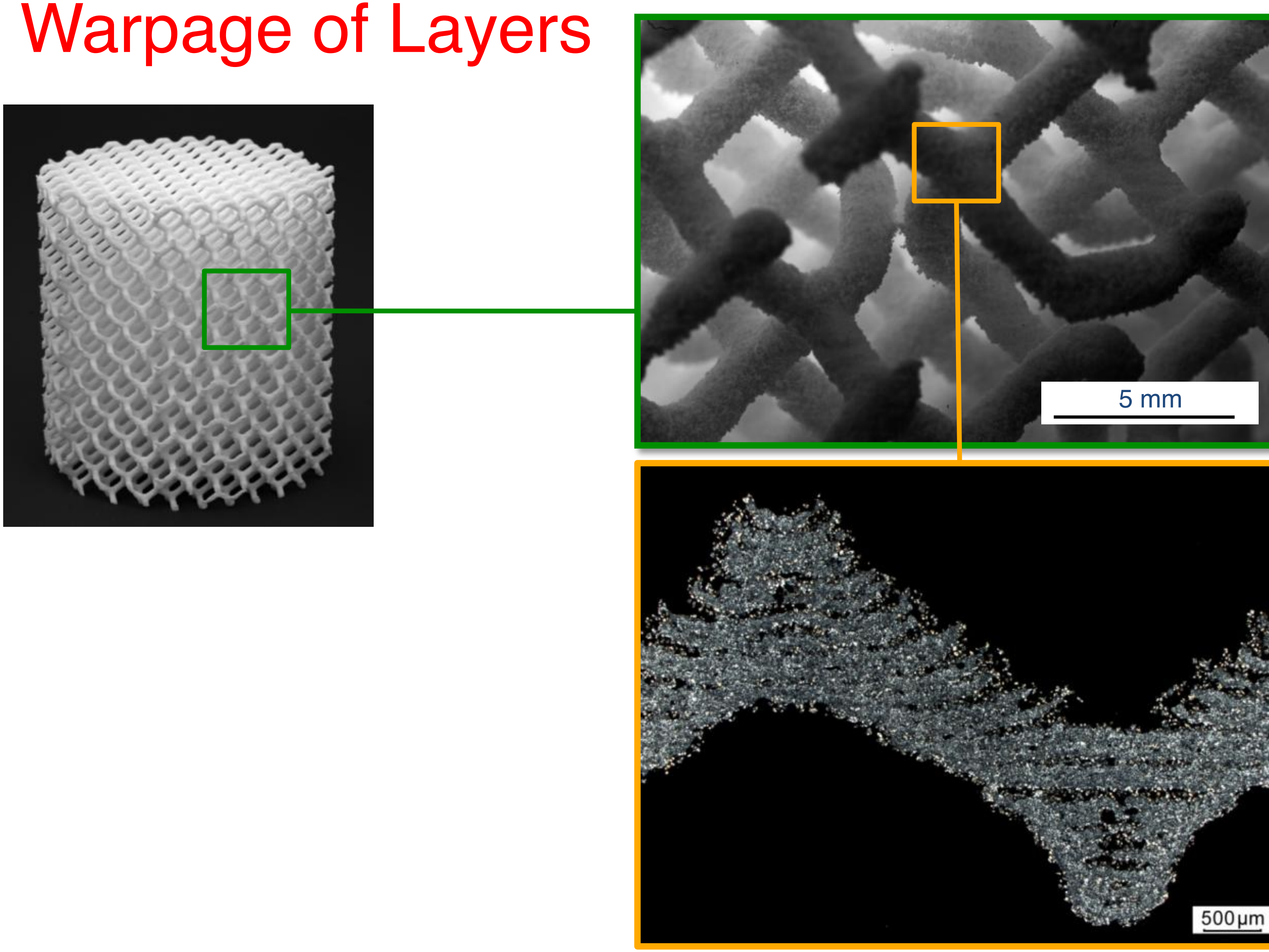
Thermal Process Window for SLS

Isothermal crystallization



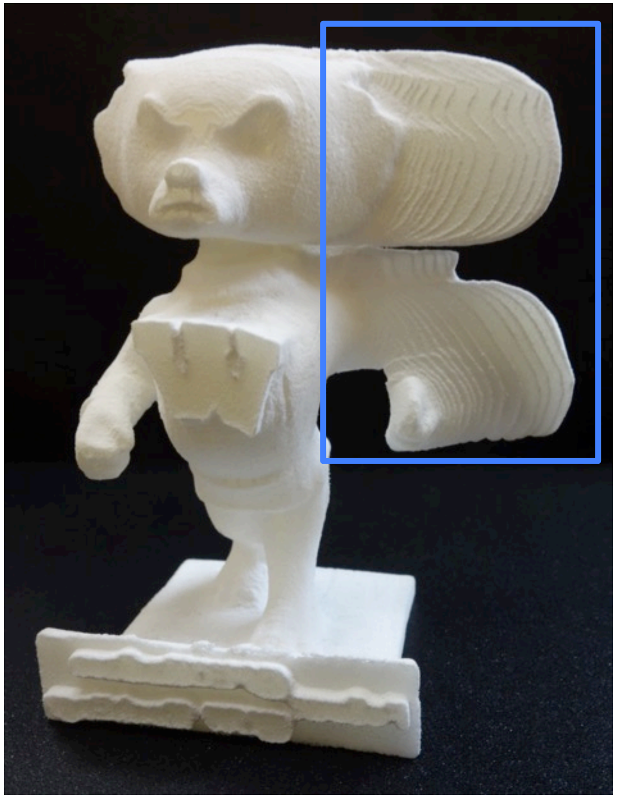
Based on: DIN EN ISO 11357-1

Warpage of Layers



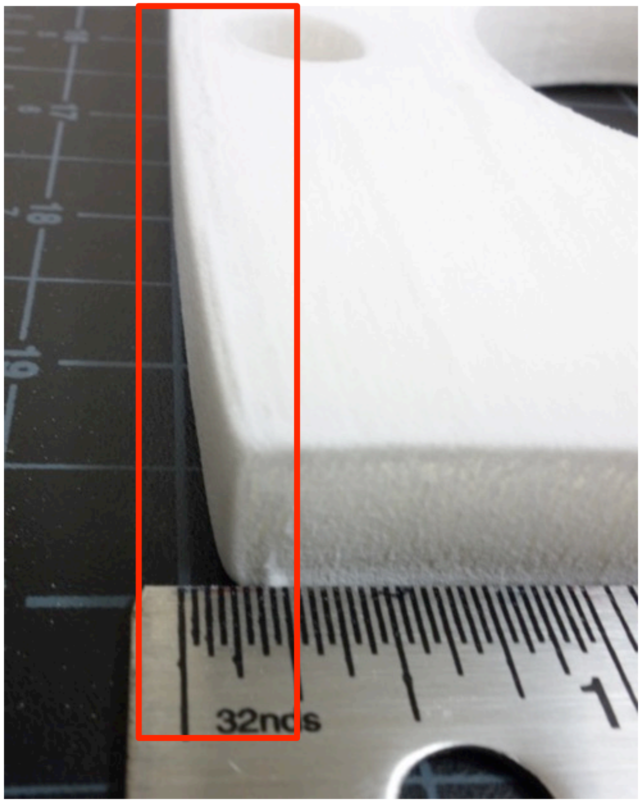
Curling

Displacement and defect



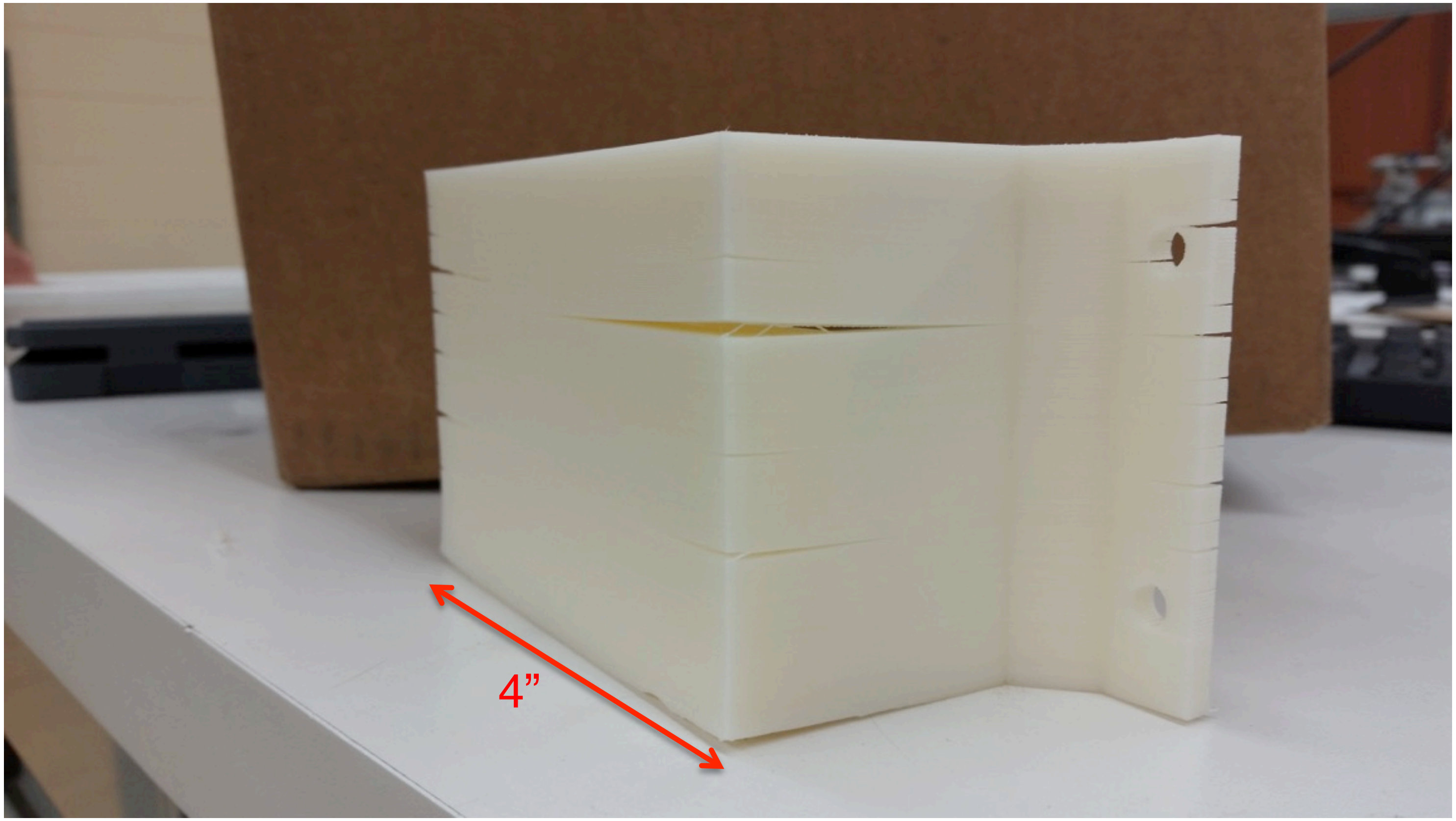
Displacement of the part position

Warpage in the first section of a part



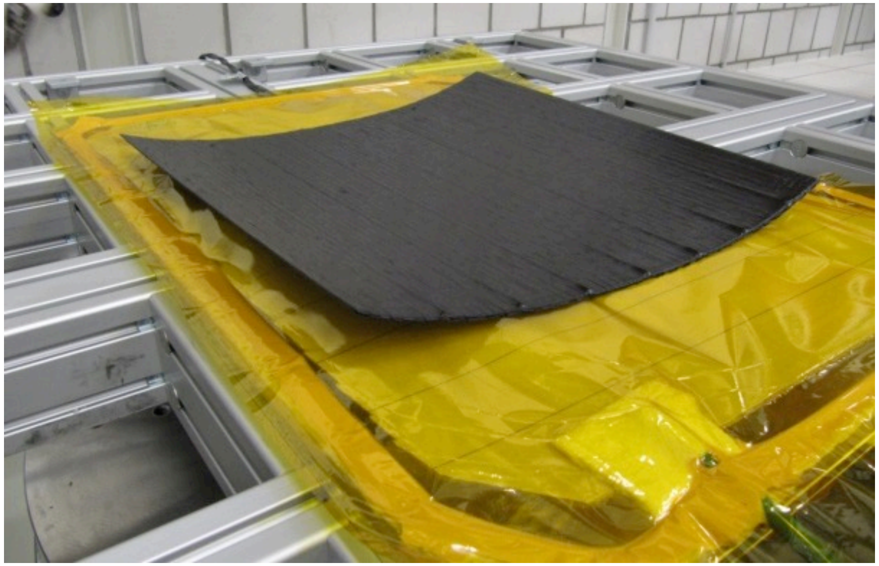
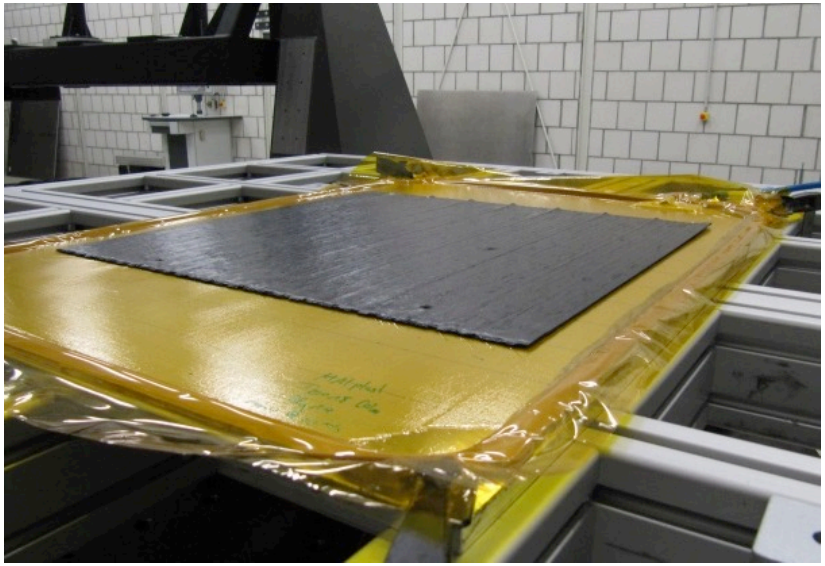
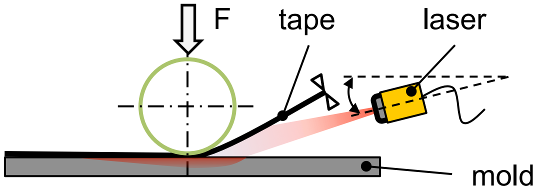
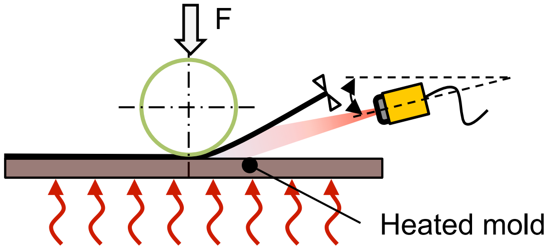
Warpage in FDM

Cooling effects in massive parts



Print parameters: 230°C nozzle temperature, 120°C bed temperature, 40mm/s travel rate, 50% infill, 2 shells

Warpage in AFP
Heated vs. cold mold

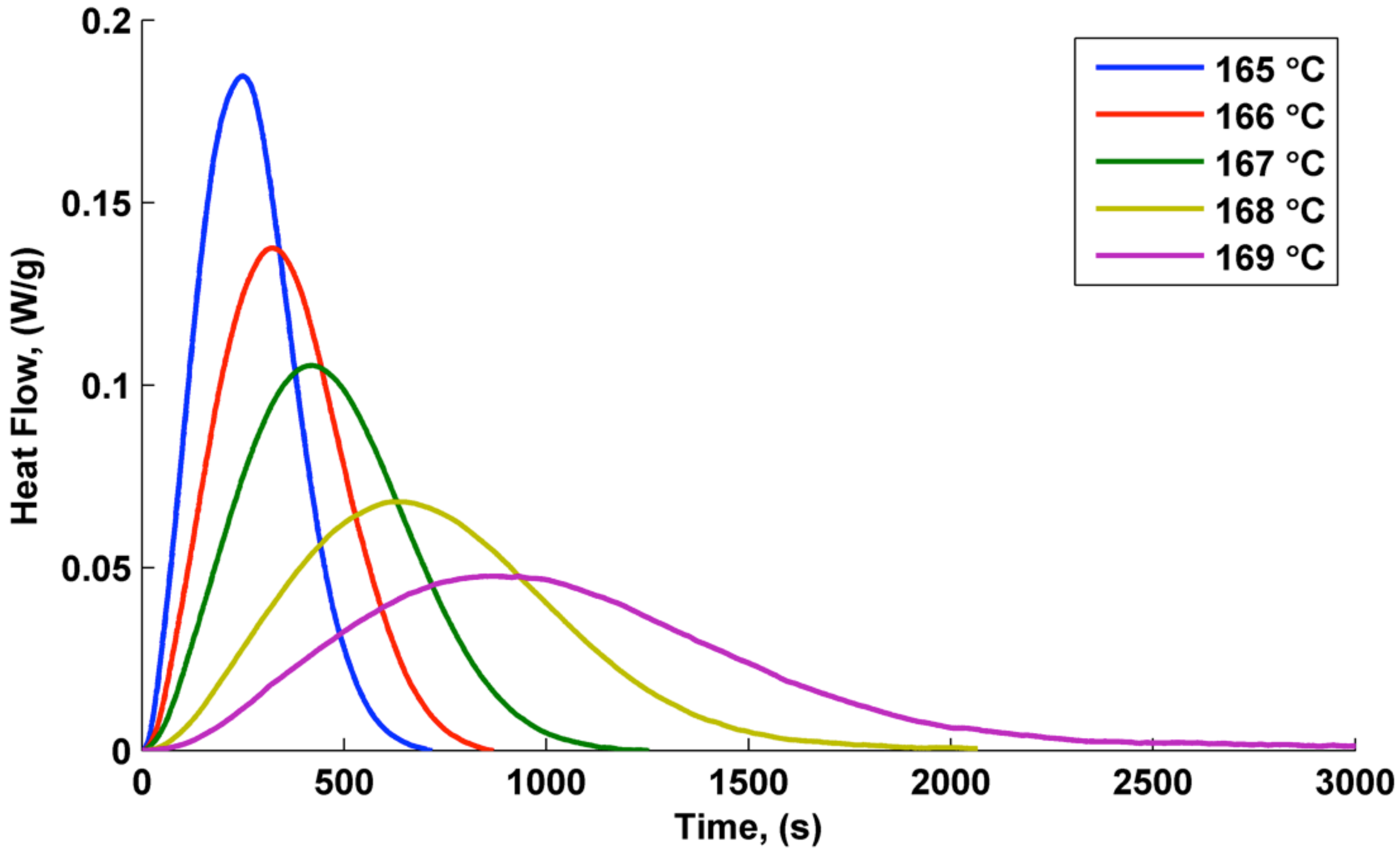
Layup on cold mold	Layup on heated mold
	
	

Zenker, 2014

Isothermal crystallization

DSC

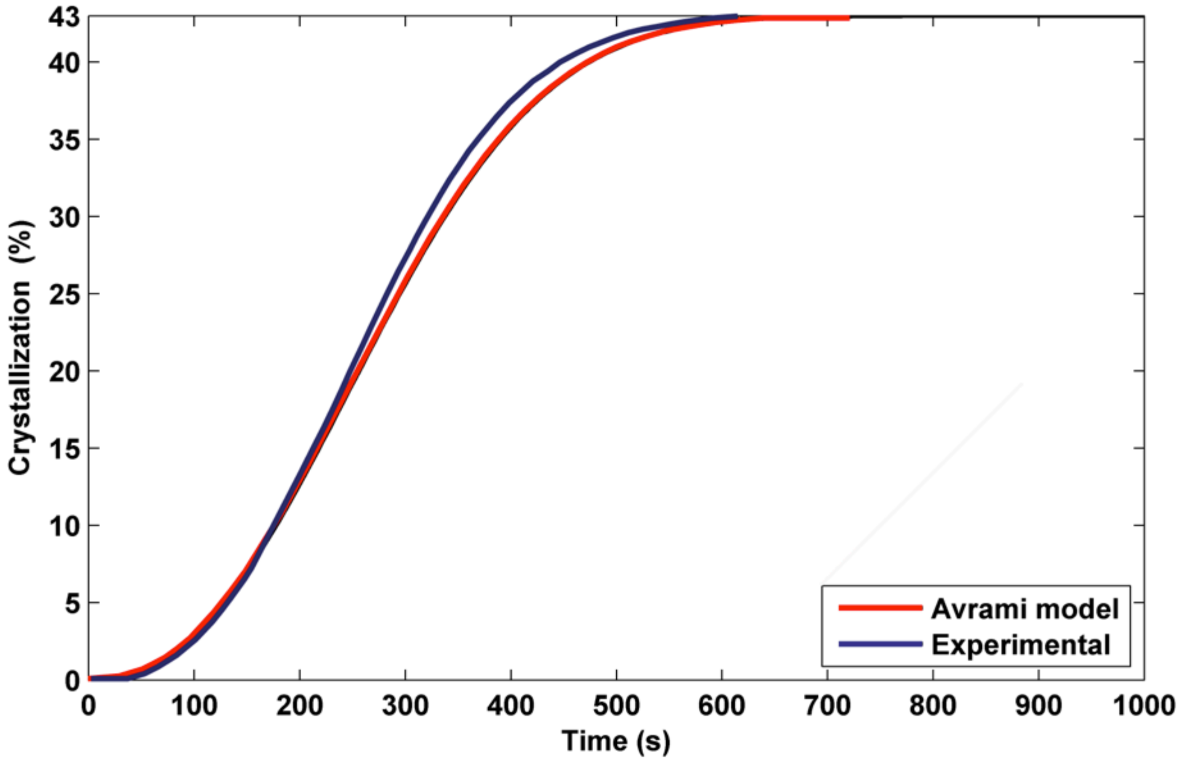
Polyamide 12 (PA 650, ALM)



Isothermal crystallization

Avrami model

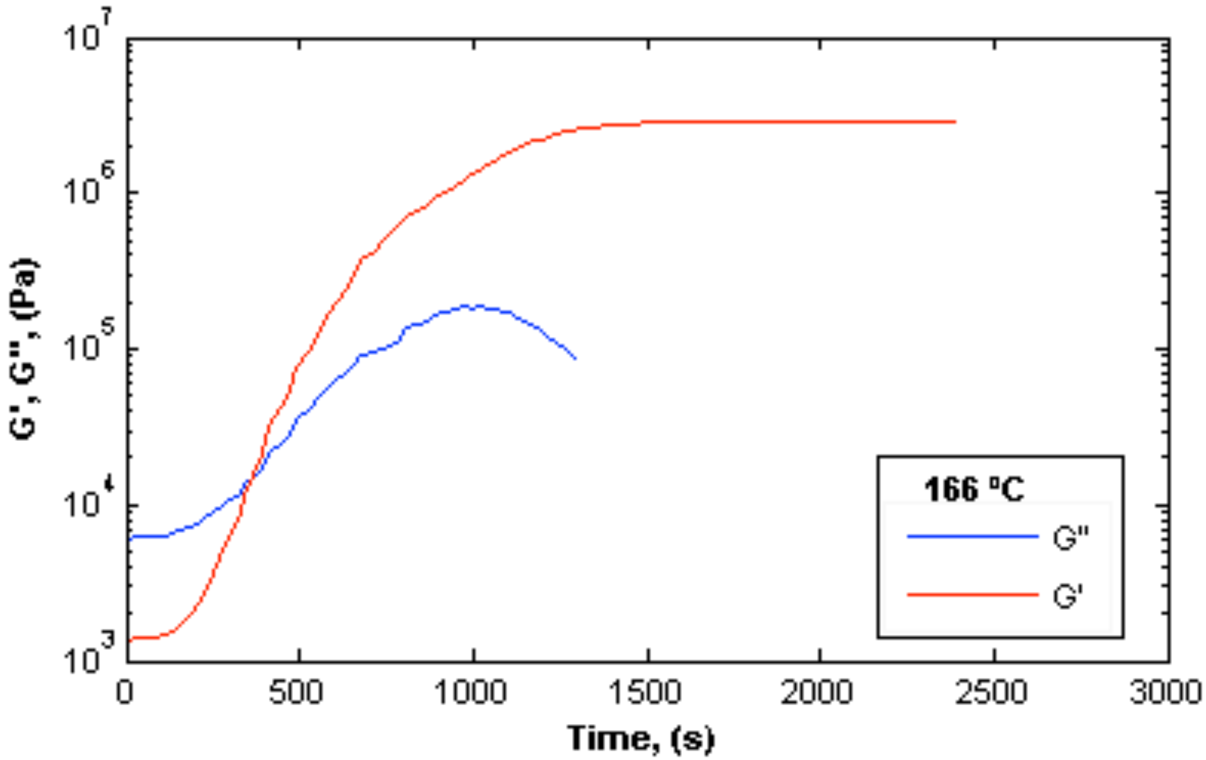
$$\alpha(t) = 1 - e^{-kt^n}$$



Elastic Modulus

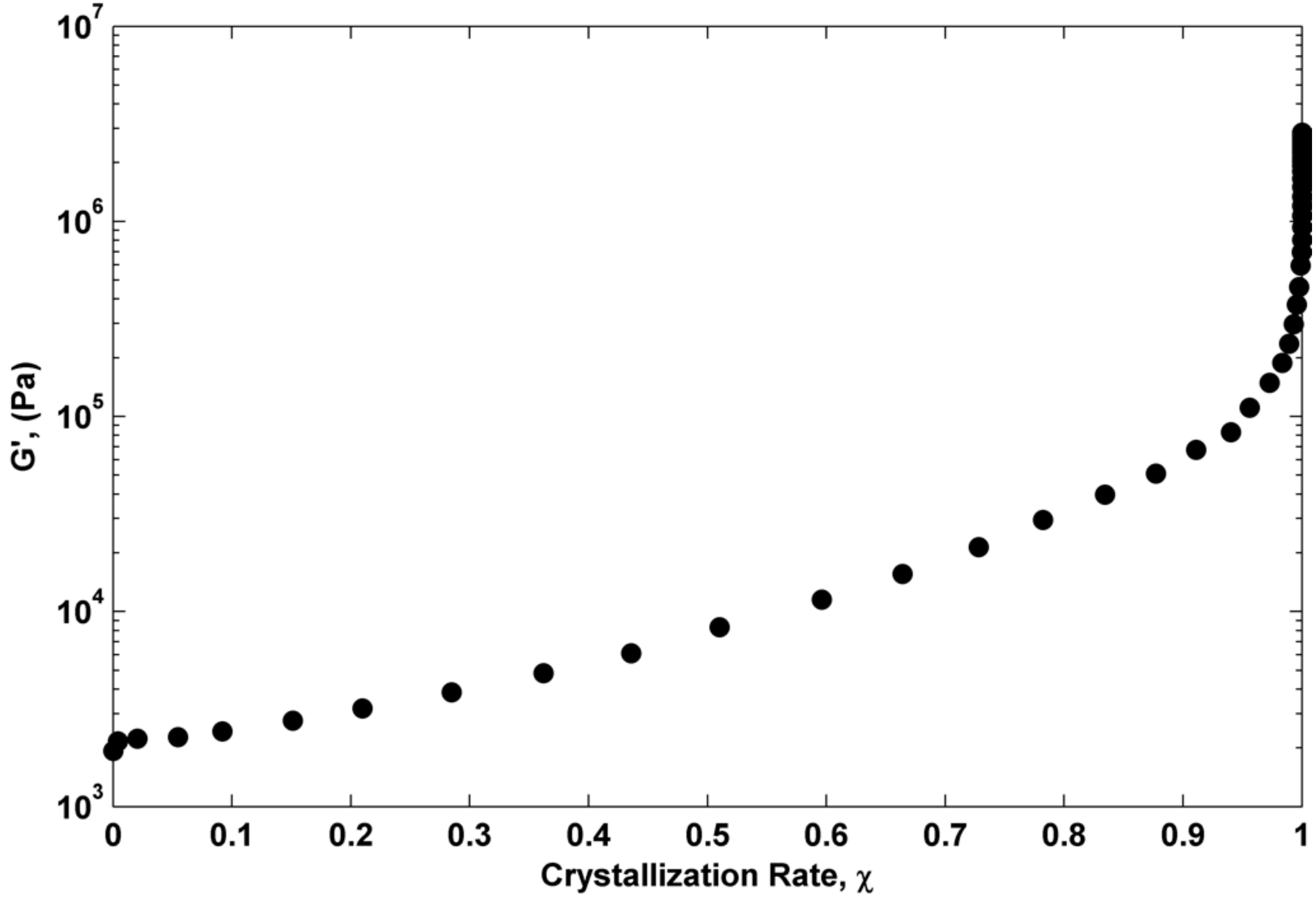
Rheology: Measurement in oscillation

- Cone-plate rheometer
- Modulus development at 0.1 Hz
- G' and G''



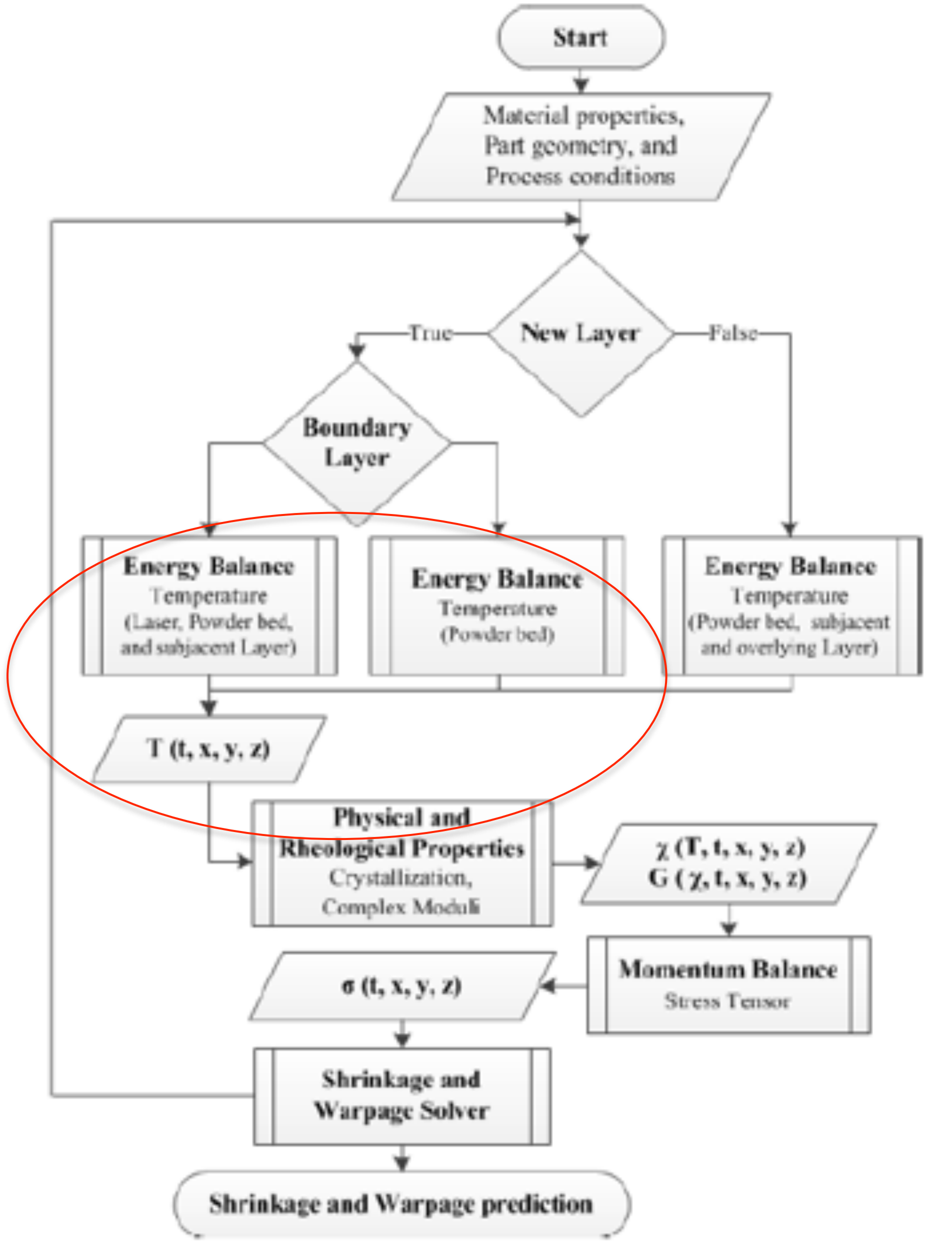
Prediction of residual stresses

Correlation of modulus and crystallization



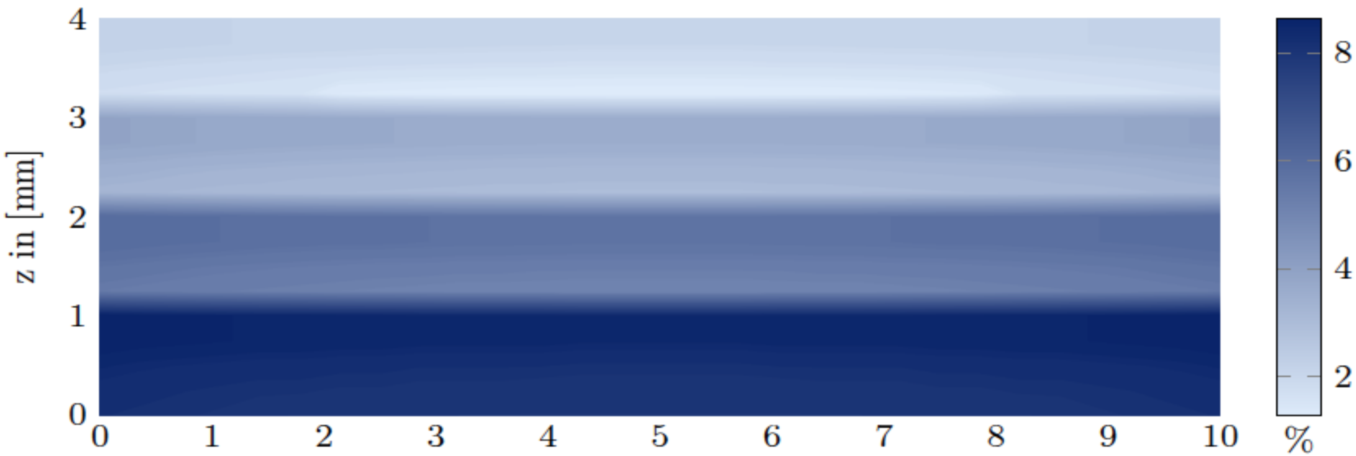
Simulation

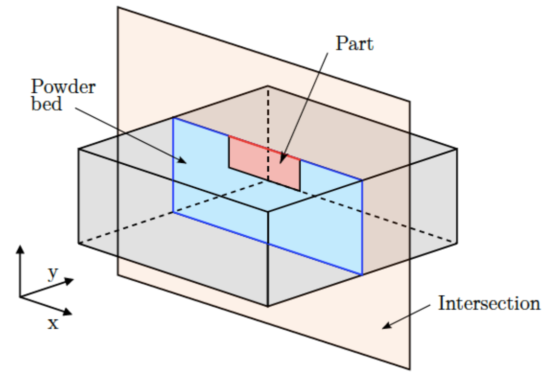
- Prediction of shrinkage and warpage using advanced computing simulations
- Application to thermal processes

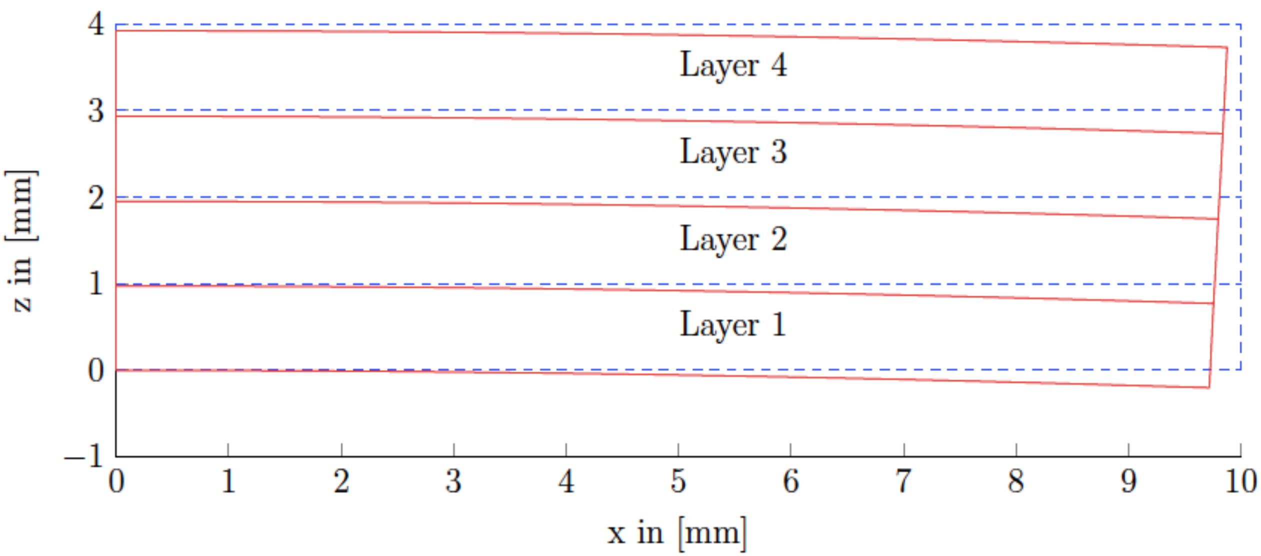


Shrinkage and warpage

First results with Matlab



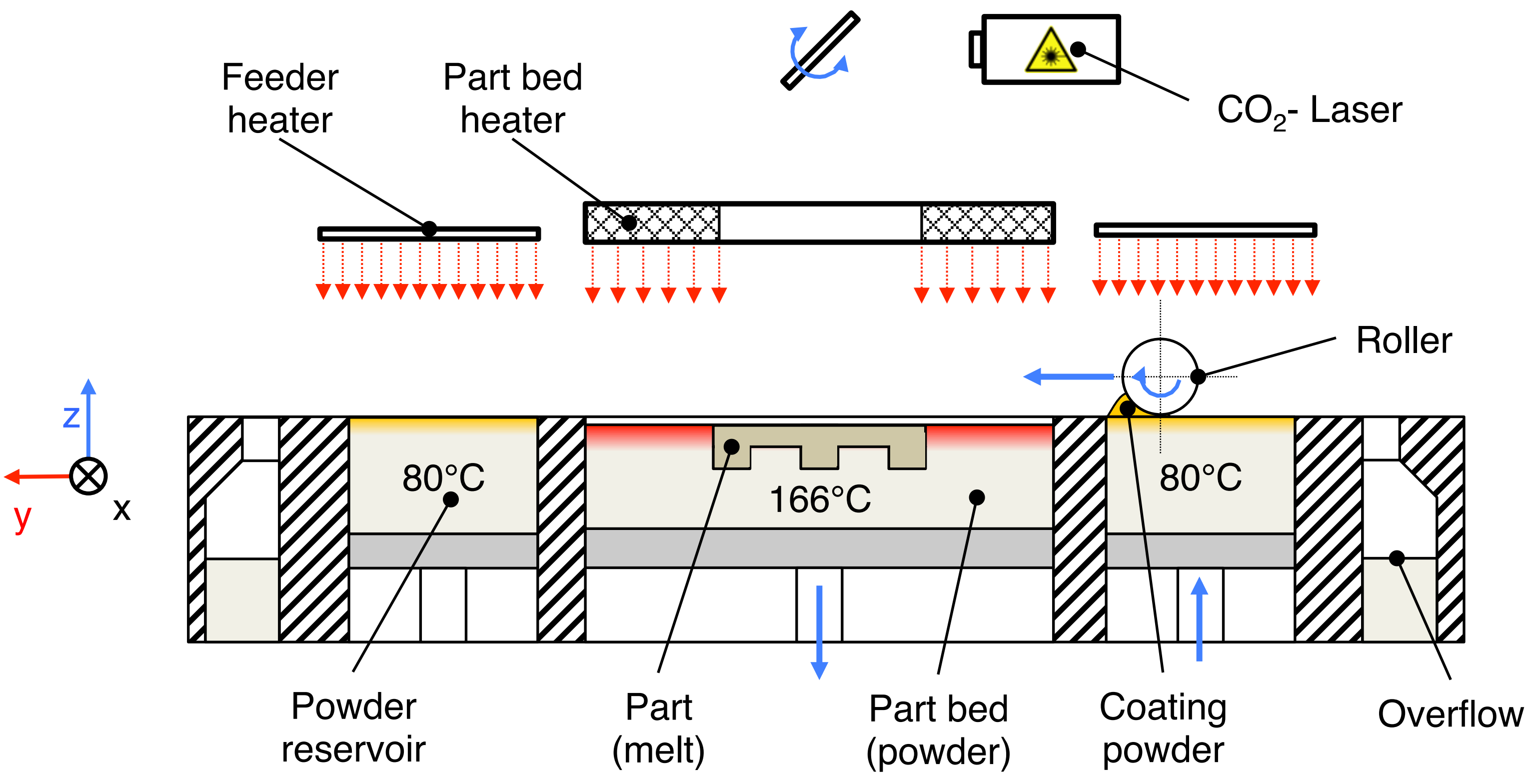




BUT…what does the temperature field look like?

Example: temperature field during coating

Major Components of a SLS System (DTM 2500)



Based on: VDI - Guideline 3404 [1]

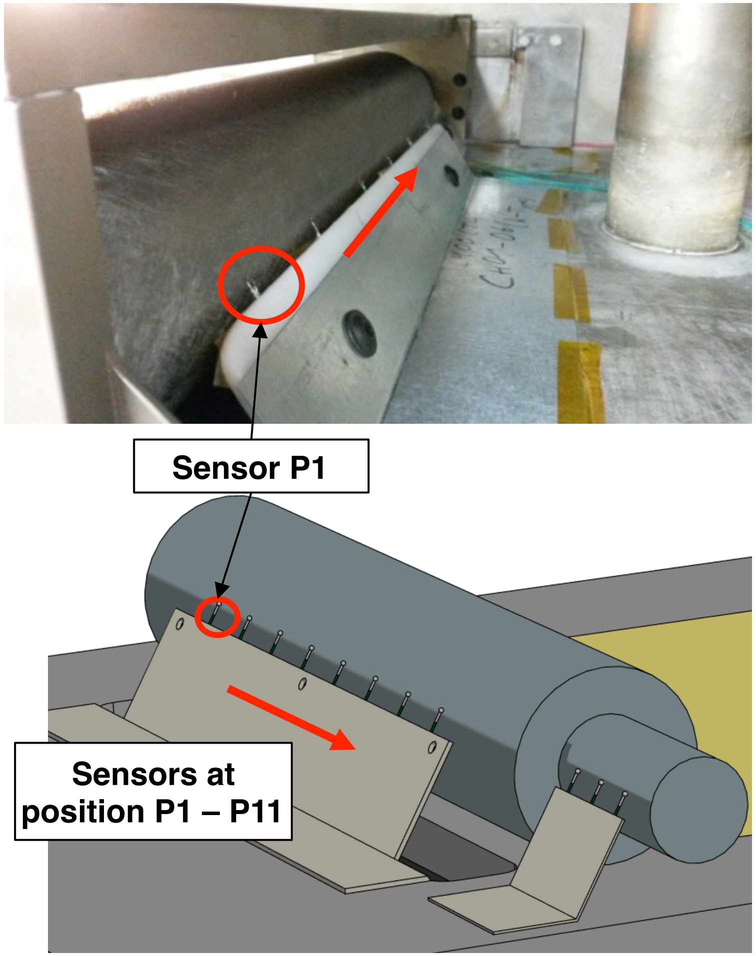
Data acquisition
Temperature measurements

Data acquisition equipment:

- NI-9211/NI-9214®
- 11 K-type thermocouples
- LabVIEW 2013®

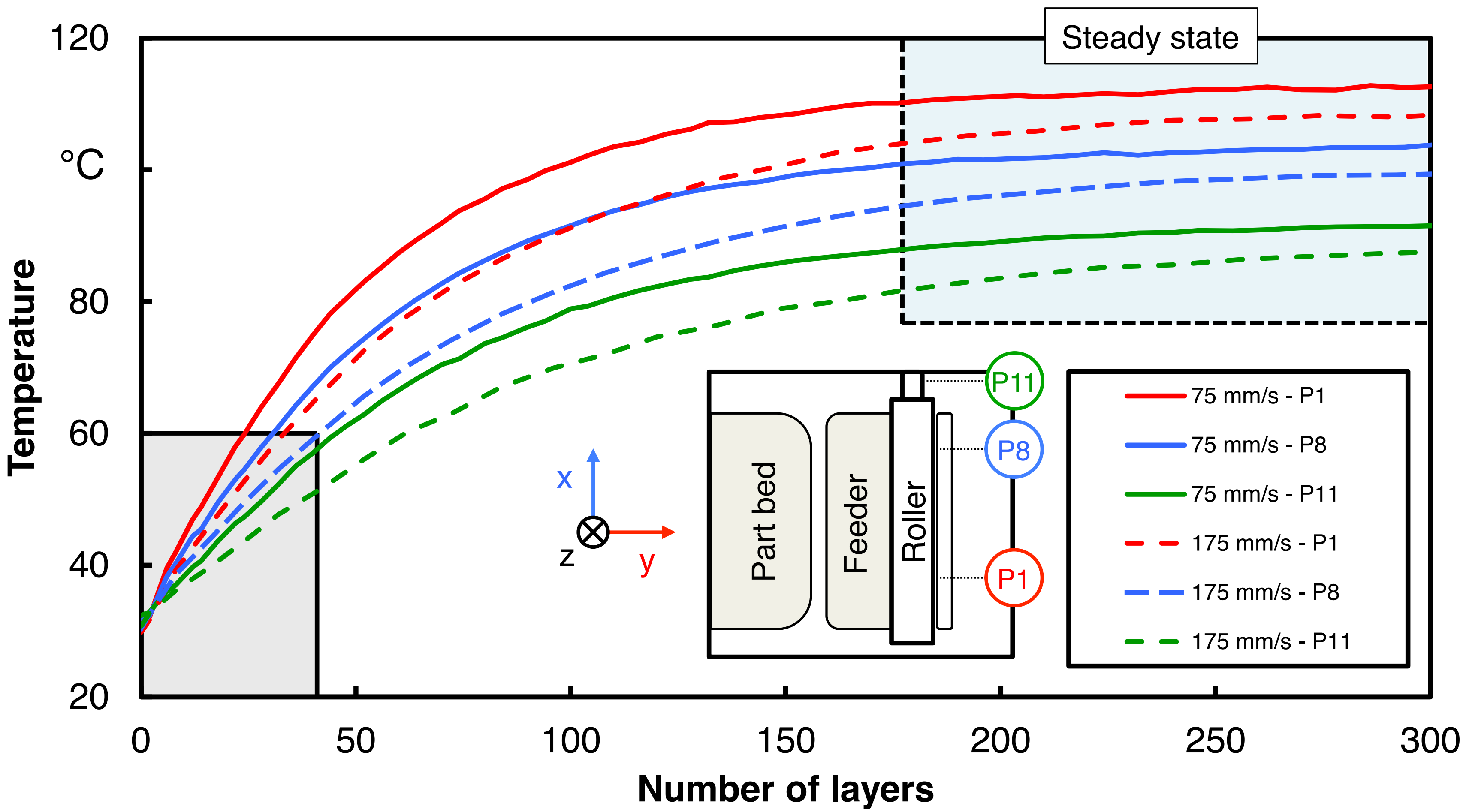
Process settings:

- PA 12 powder (PA 650®)
- $T_{part\ bed}$ = 166 °C
- T_{feeder} = 80 °C
- v_{Roller} = 75 / 125 / 175 mm/s



Data acquisition

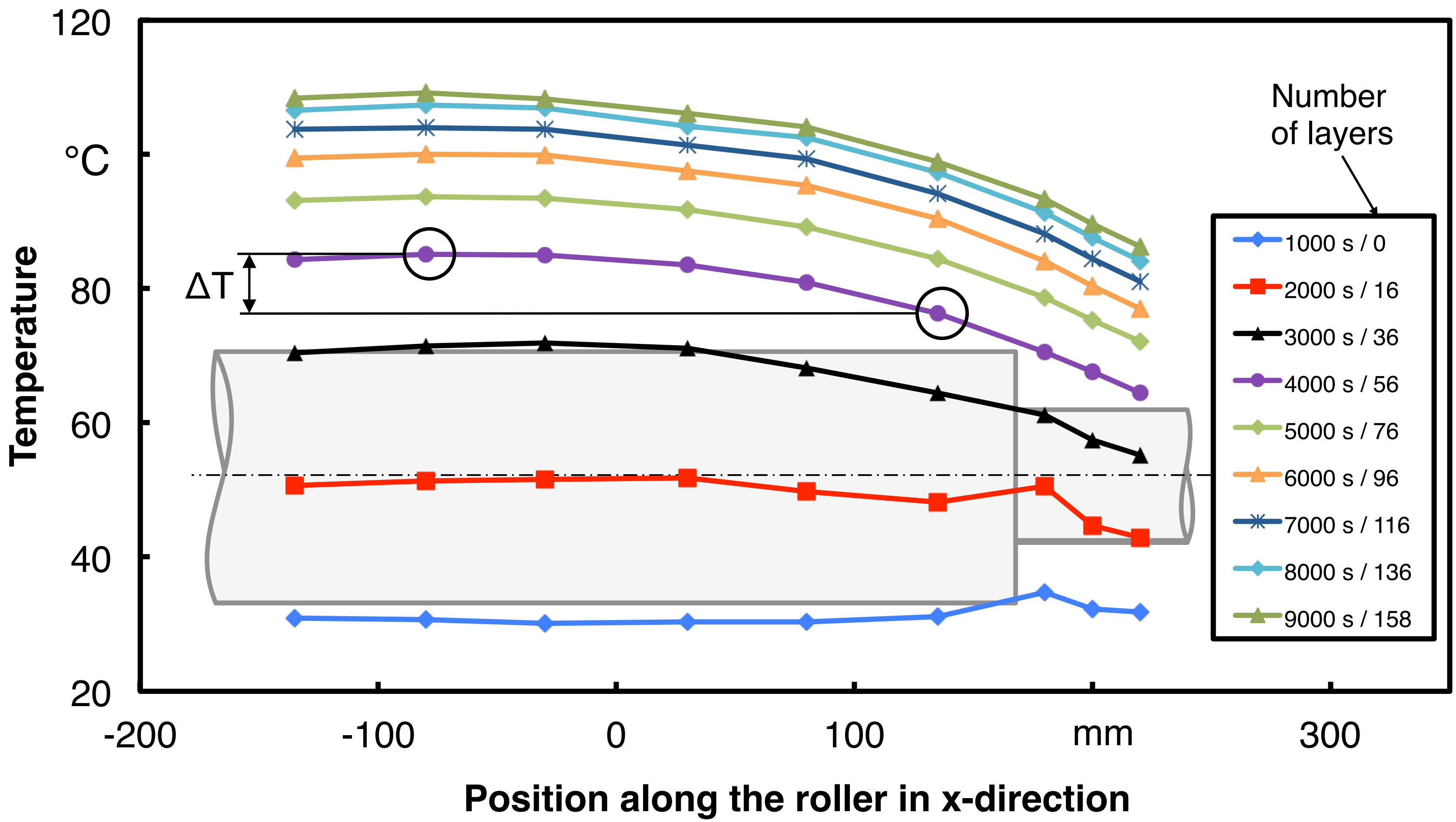
Roller temperature for different roller speeds



Lassmann, 2015

Data acquisition

Temperature distribution along the roller



Lassmann, 2015

Modeling and Simulation

Task Preprocessing – Model setup

Geometrical model

e.g. dimensions of
- roller
- part bed
- powder wave

Thermal model

e.g. definition of initial and boundary conditions
- temperatures
- heat fluxes

Thermal simulation

Material model

e.g. definition of
- density
- spec. heat capacity
- thermal conductivity

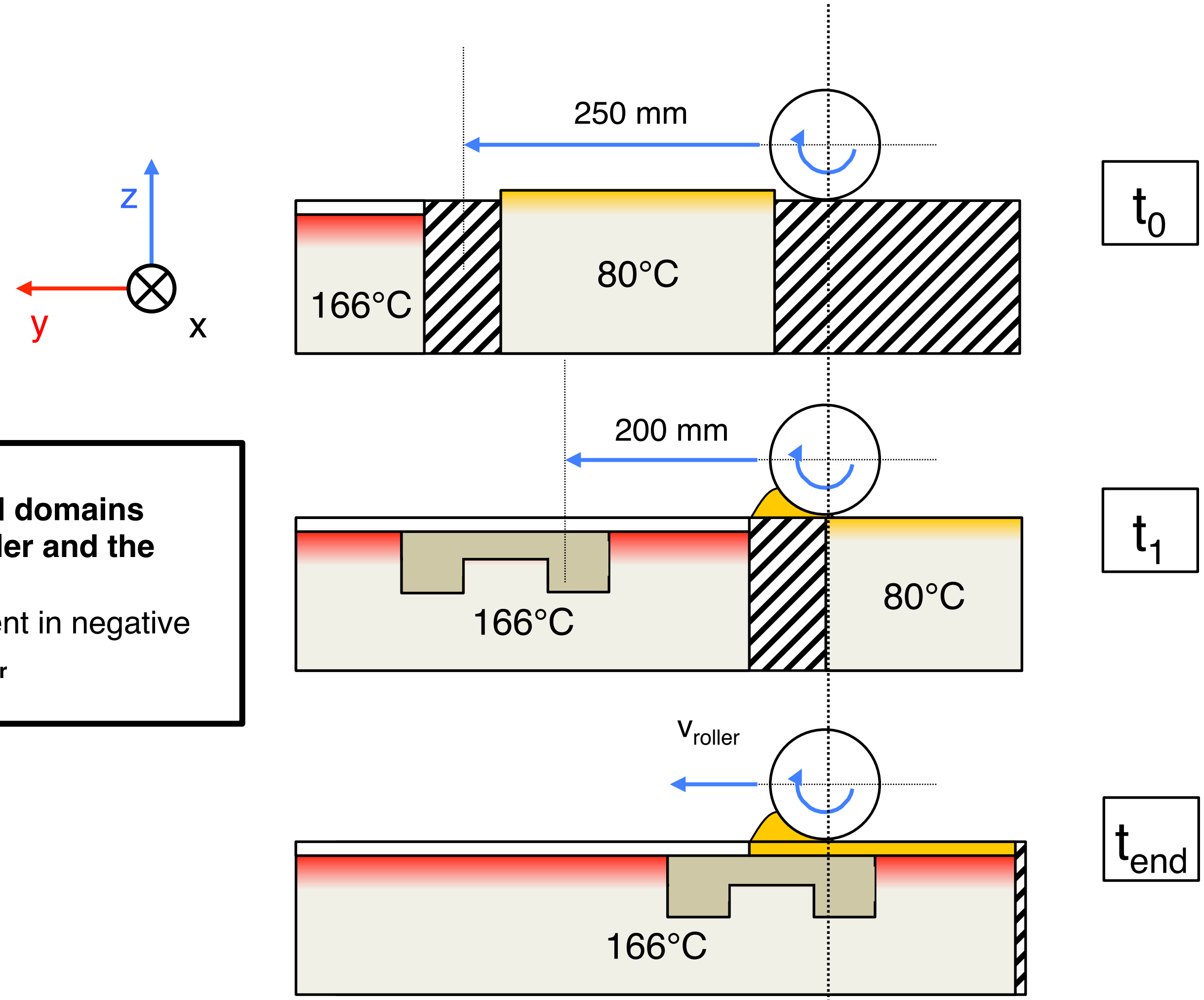
Kinematic model

e.g. definition of
- moving domains
- points in time for boundary conditions

Based on: Experimental data / Literature data & assumptions / machine data

Modeling and Simulation

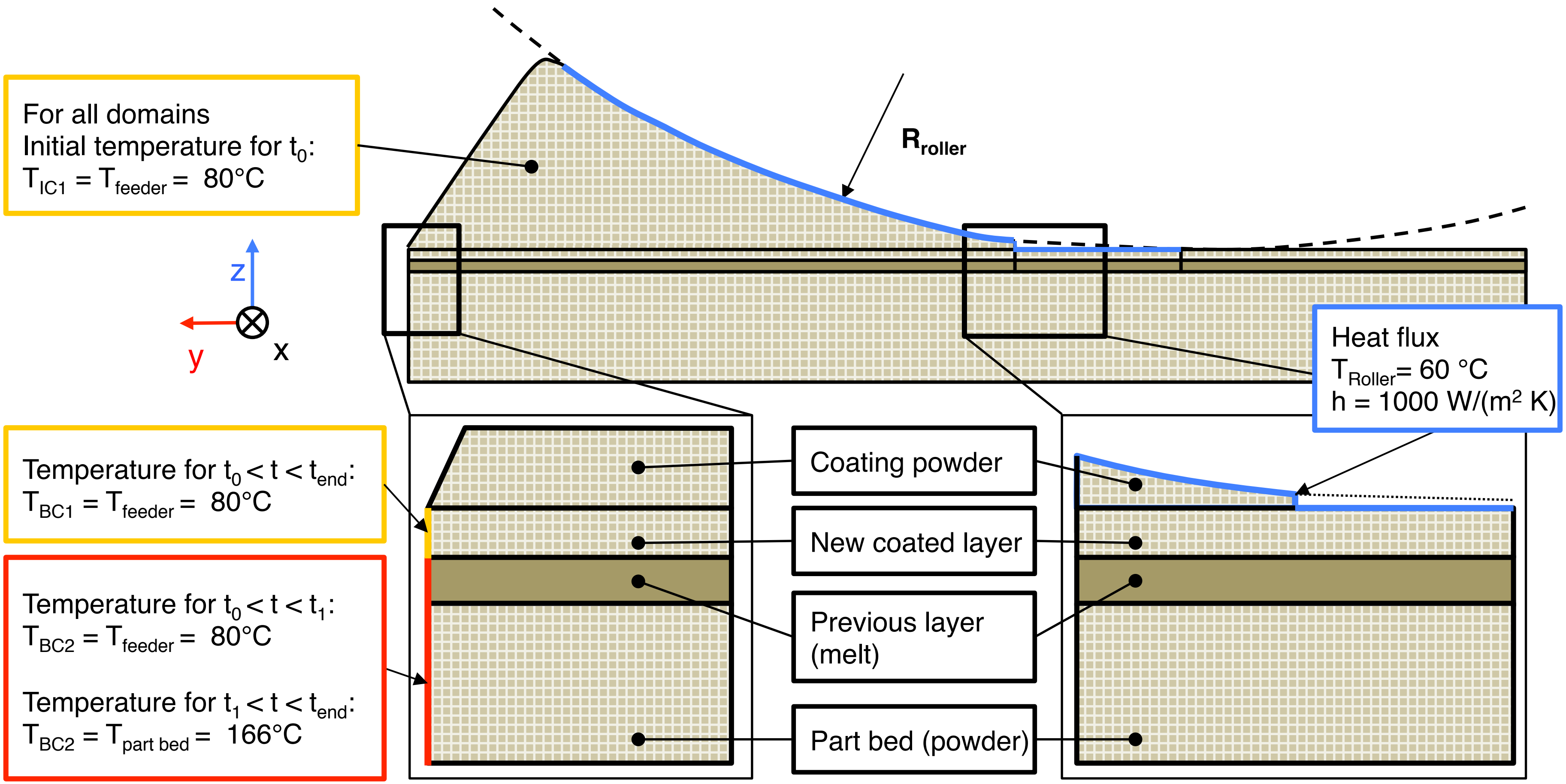
Kinematic model



Velocity field for all domains underneath the roller and the coating powder:
Translation movement in negative y-direction with $\mathbf{v}_{\mathbf{roller}}$

Modeling and Simulation

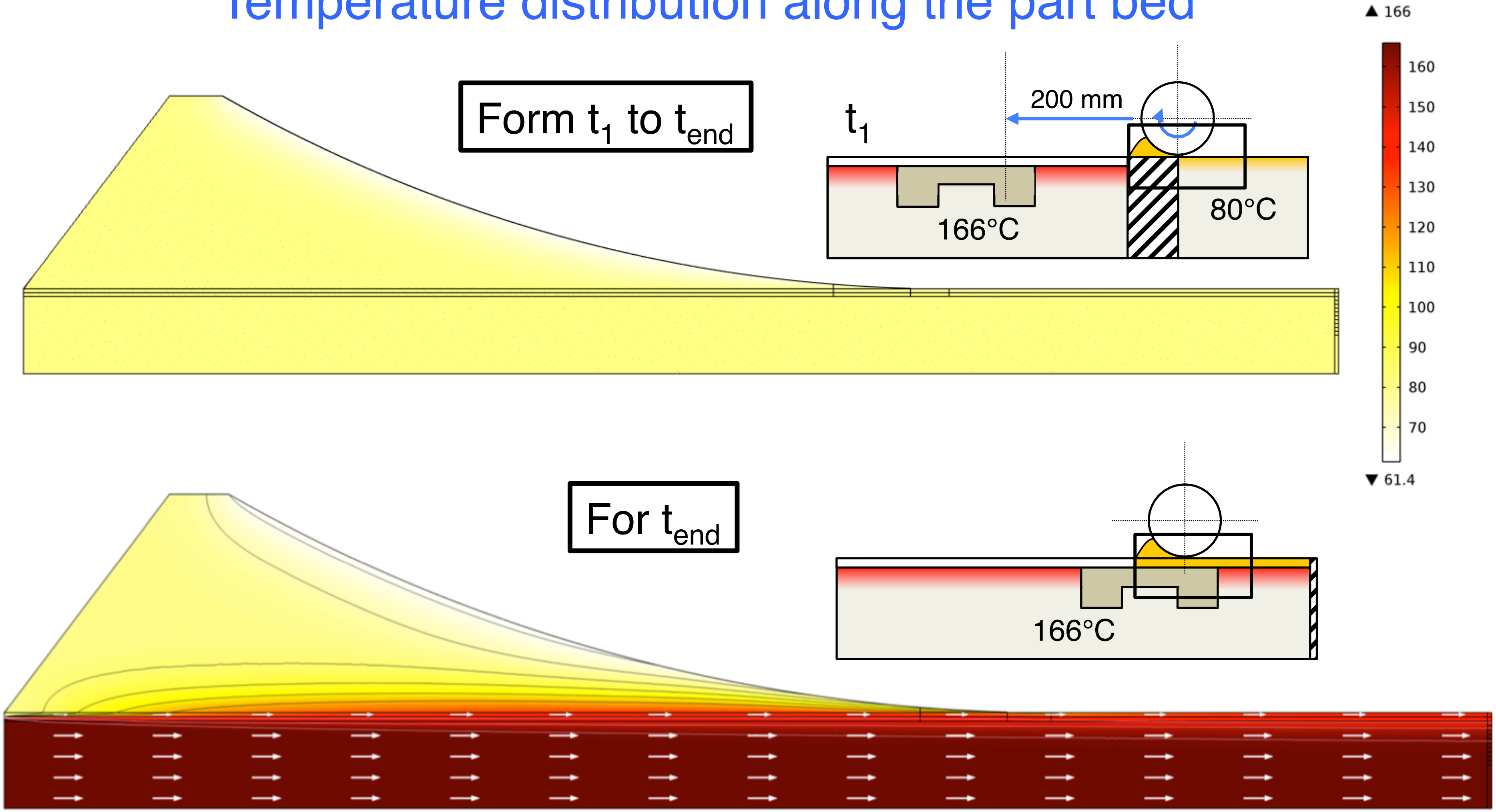
Geometrical and thermal model



BC: Boundary condition IC: Initial condition

Evaluation

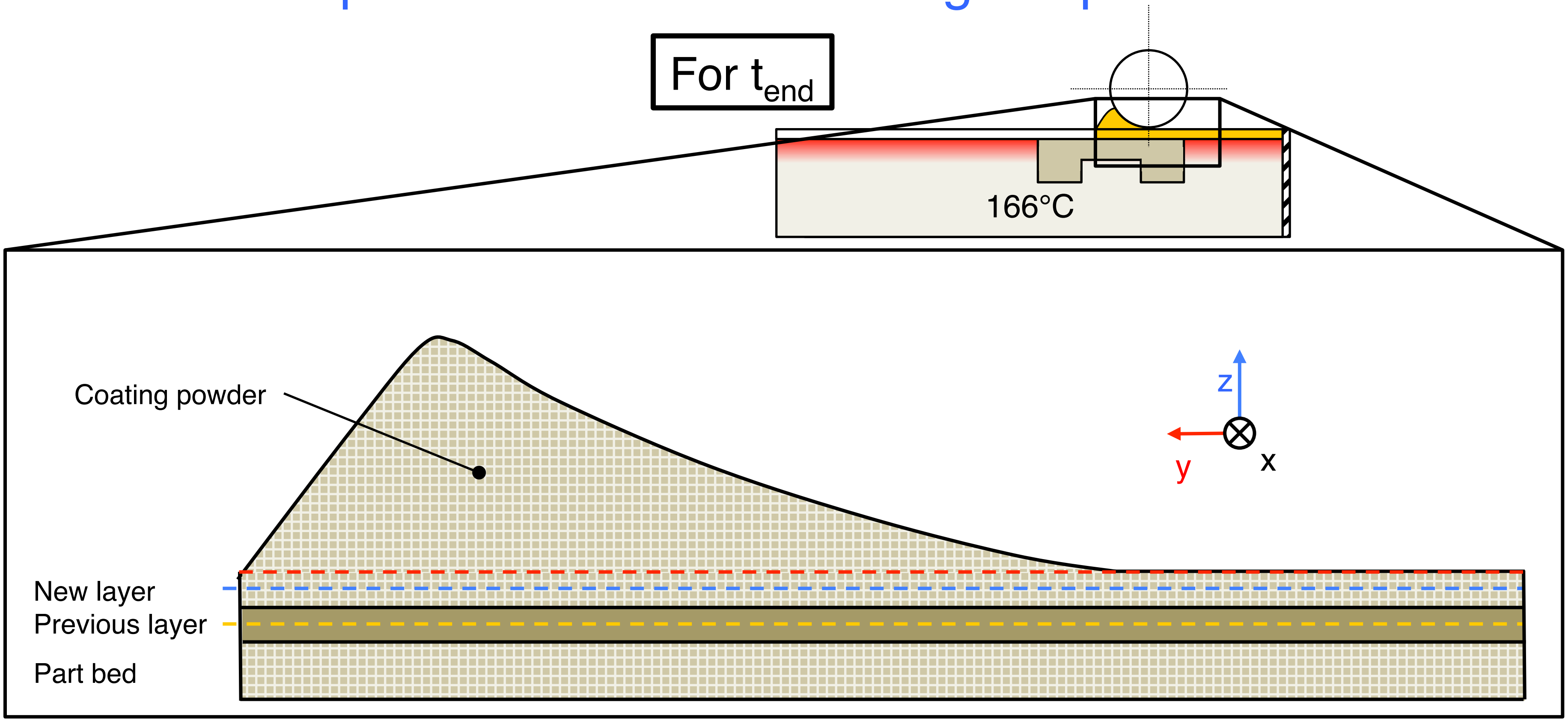
Temperature distribution along the part bed



Lassmann, 2015

Evaluation

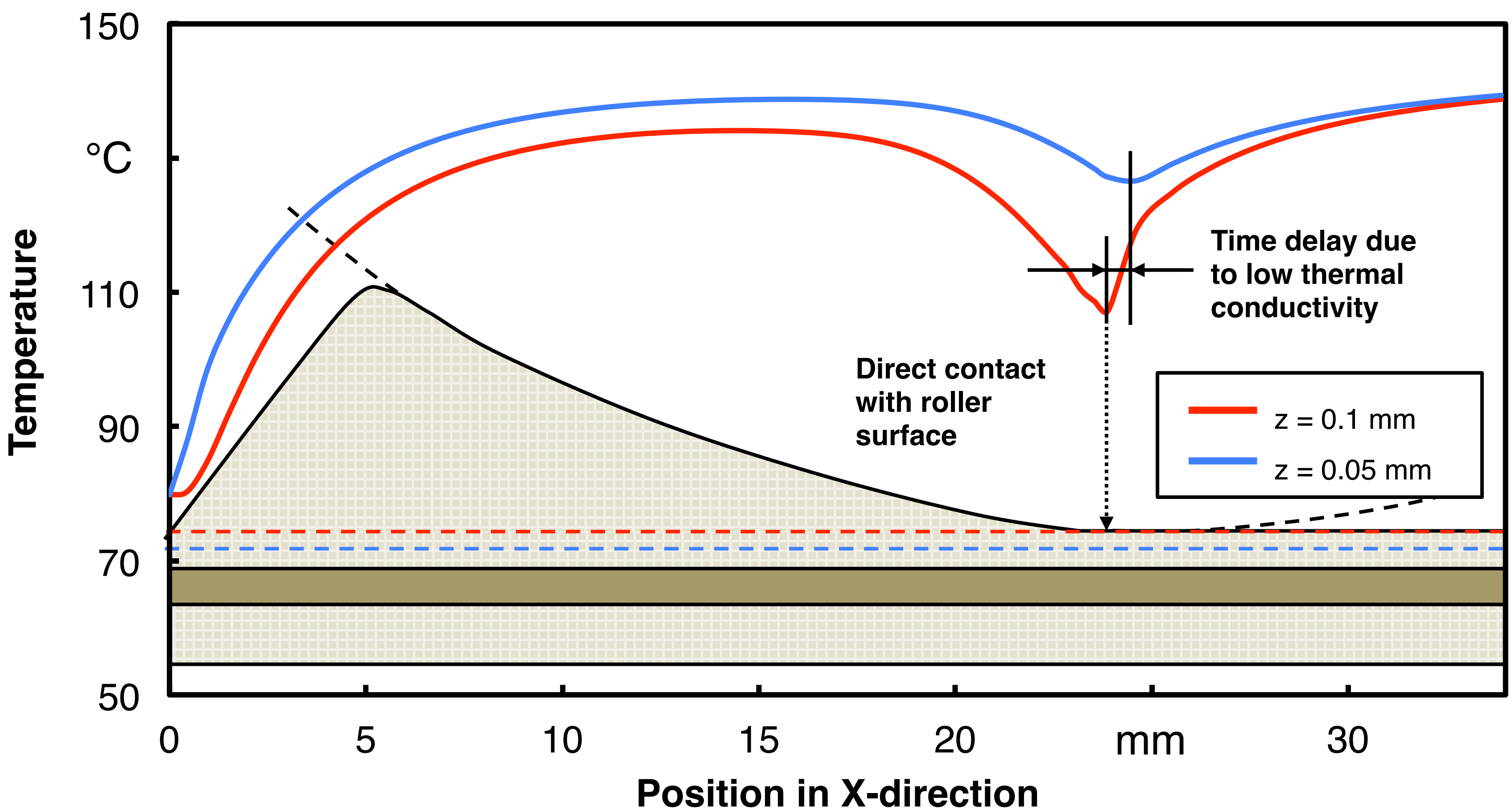
Temperature distribution along the part bed



Lassmann, 2015

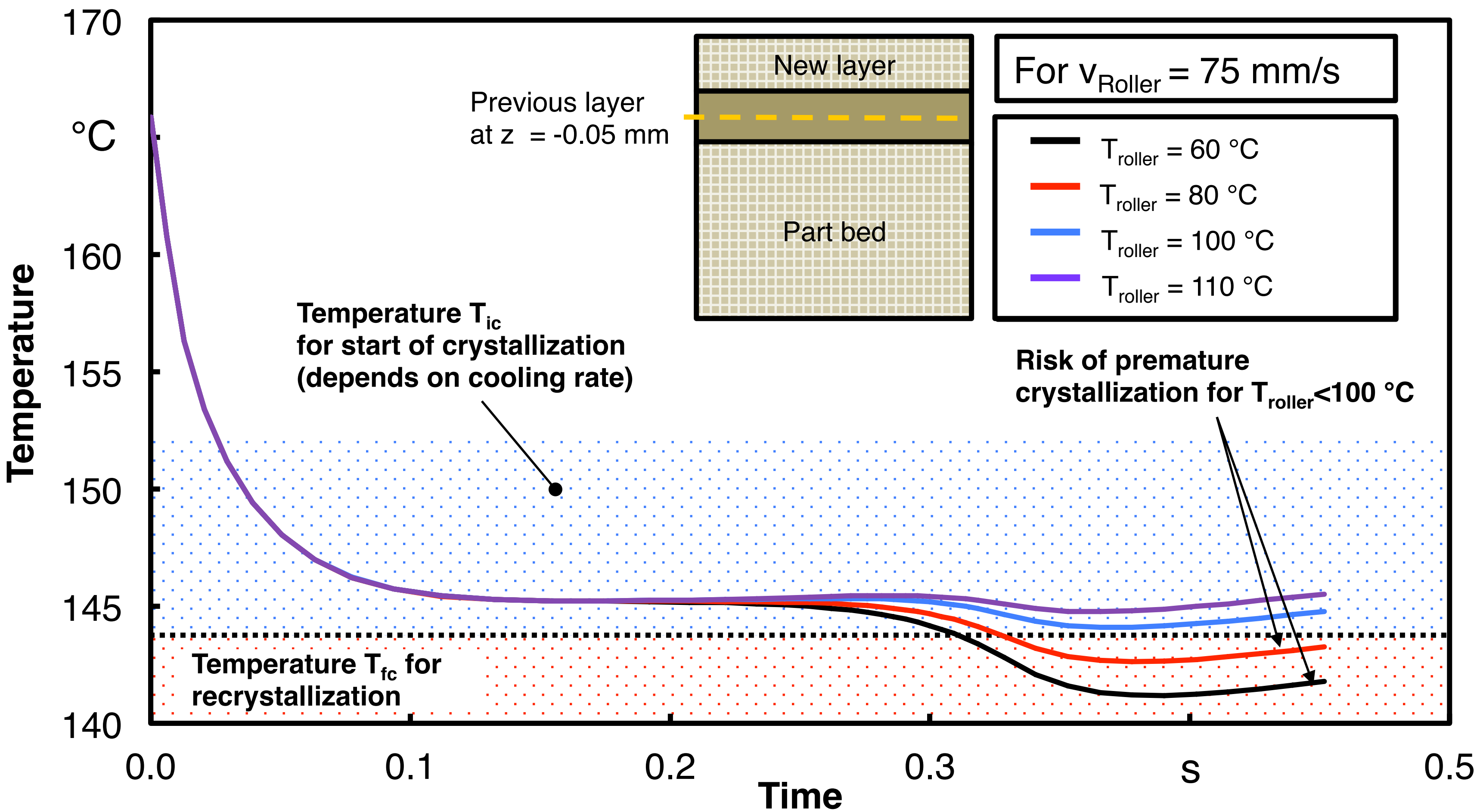
Evaluation

Temperature distribution in the new layer



Evaluation

Influence of the roller temperature



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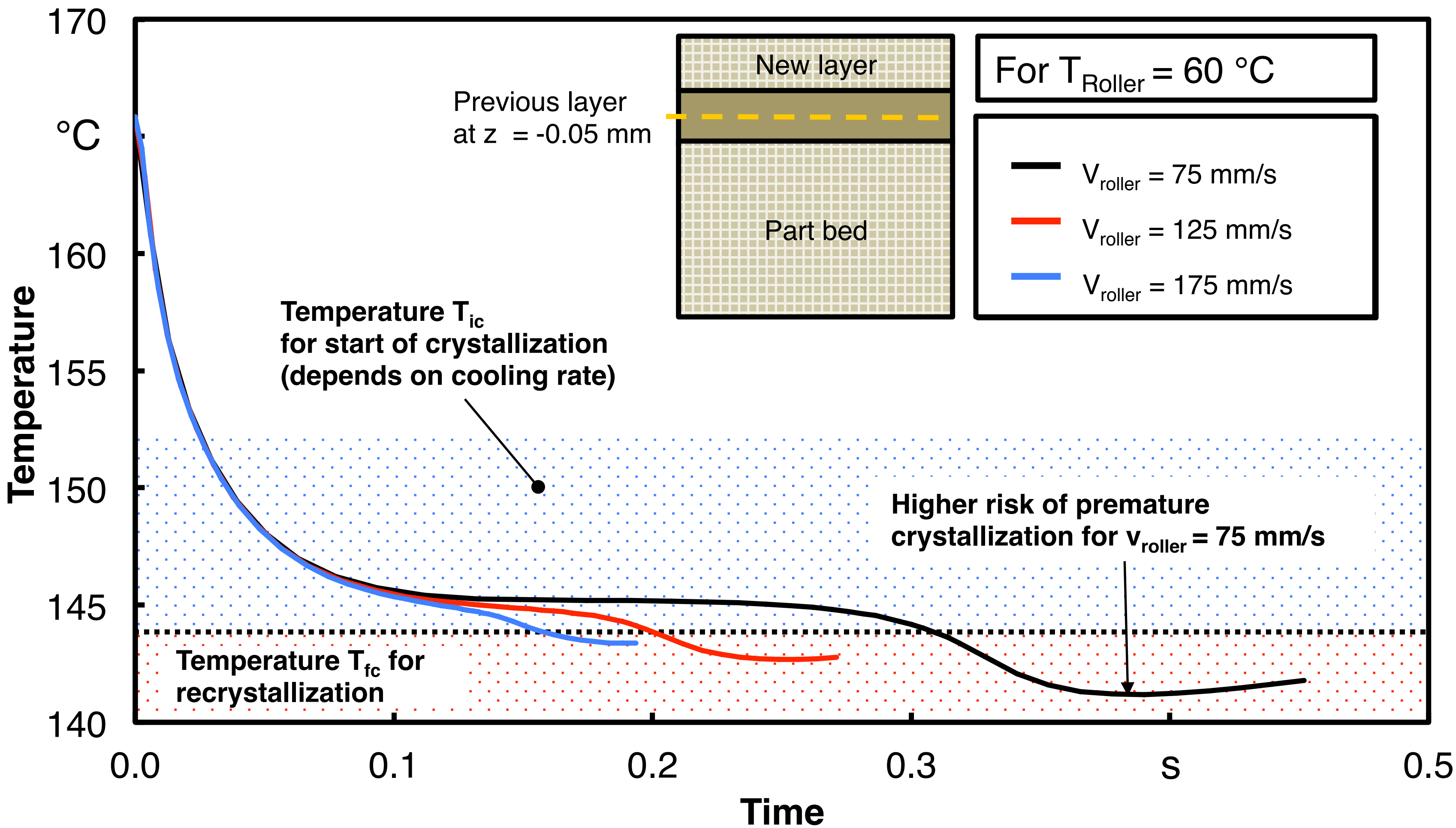
Evaluation

Temperature vs. time in the scanned layer



Lassmann, 2015

Online-Monitoring of Phase Transitions in Thermoplastics

Dielectric Analysis on PA6 and PPS

NETZSCH

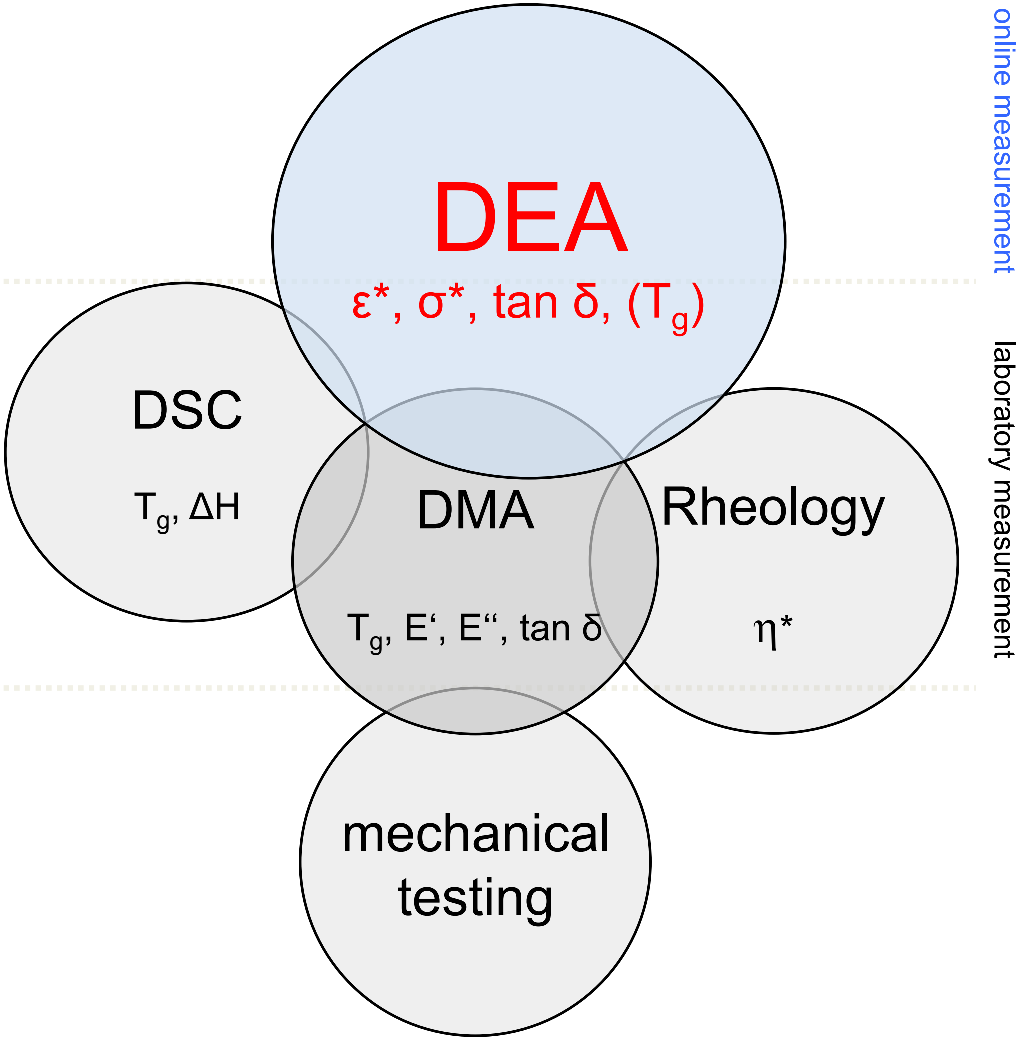
Polymer Engineering Center
University of Wisconsin-Madison

Relevance of DEA

electrical analysis
under temperature
(microscopic)

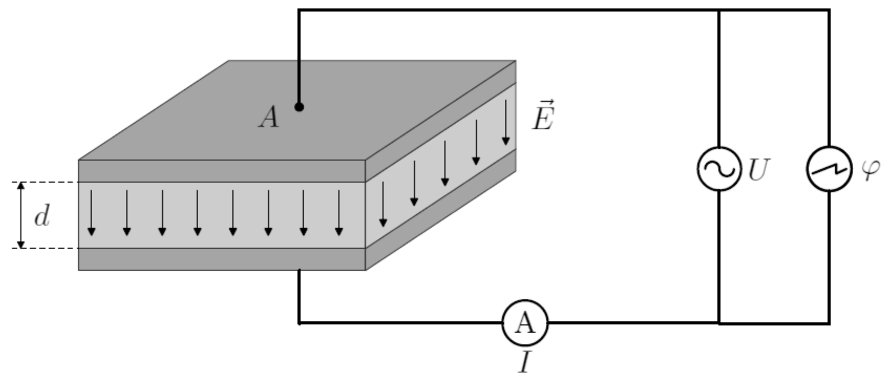
thermal analysis
(mesoscopic)

mechanical testing
(macroscopic)



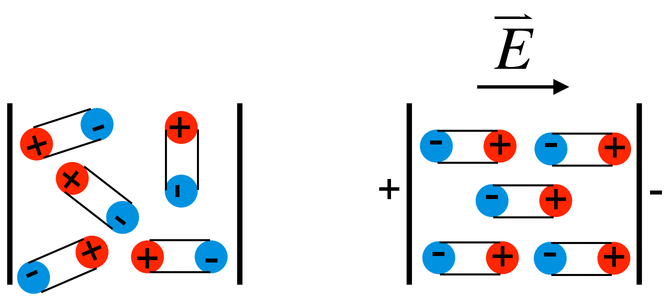
Theory

Parallel Plate Capacitor



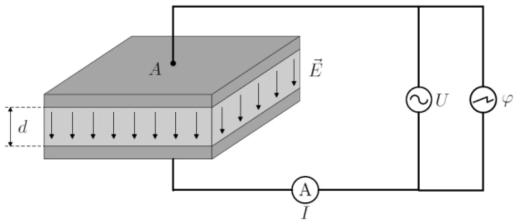
$$C^* = \varepsilon_0 \varepsilon_r^* \frac{A}{d} \xrightarrow[\text{ion conductivity}]{\text{dipole orientation}} C^* = \varepsilon_0 \varepsilon' \frac{A}{d} - i\varepsilon_0 \varepsilon'' \frac{A}{d}$$

$$\varepsilon_r^* = \varepsilon' - i\varepsilon''$$

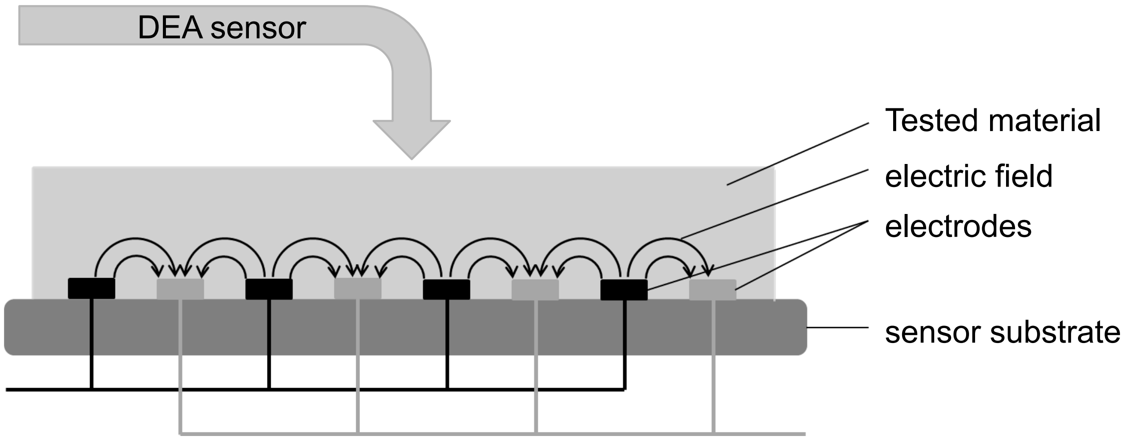


C: capacitance
ϵ_0: permittivity of free space
ϵ_r: relative permittivity of the dielectric sample
A: area of the capacitor plates
d: distance between the plates
ϵ': relative permittivity
ϵ'': loss factor

Theory in Application
DEA



parallel plate capacitor



interdigitated electrodes
(one-sided measurements)

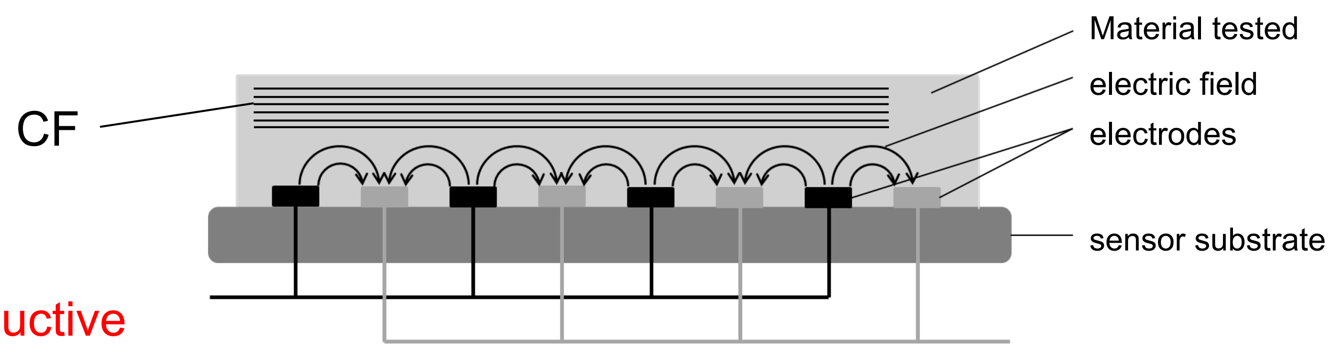
sensor design:


disposable sensor


reusable tool mountable sensor

Theory in Application

Modifications for conductive material, e.g. CF



interdigitated electrodes
(one-sided measurements)

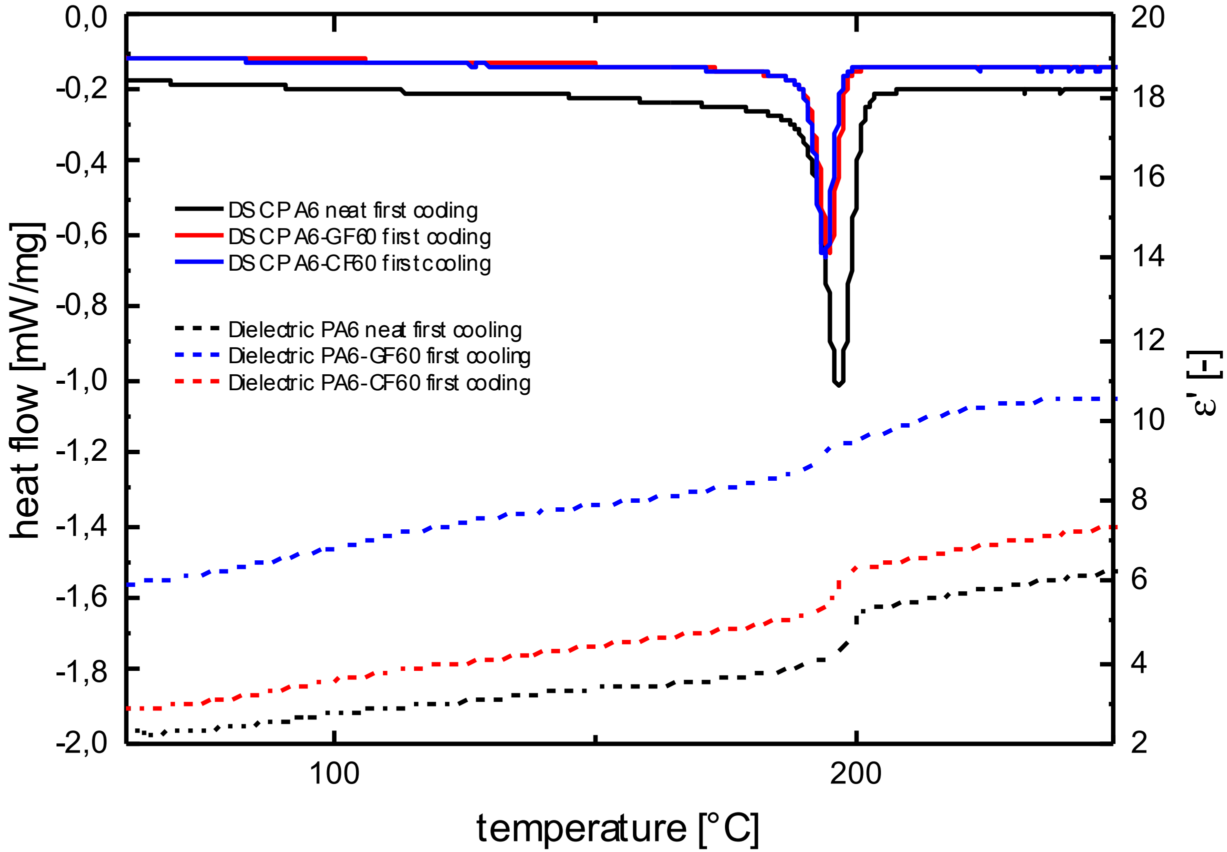
electrical conductive

short circuit

insulating / covering layer between electrodes and material

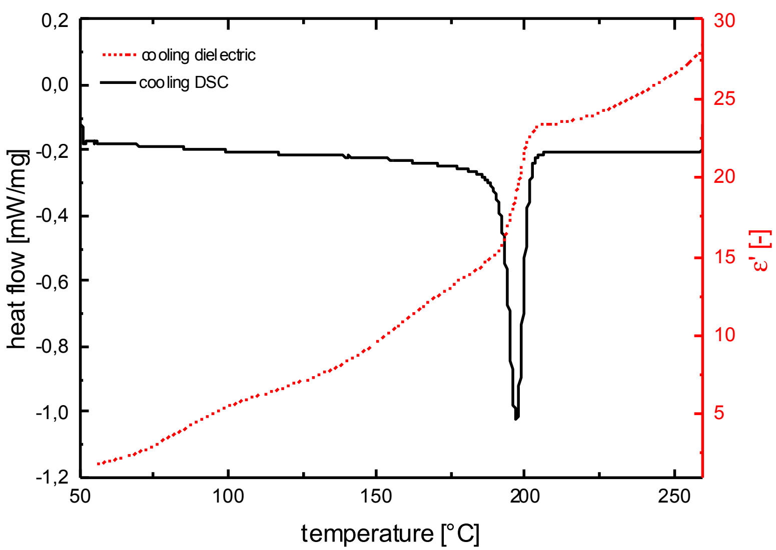
Correlation of DSC and DEA

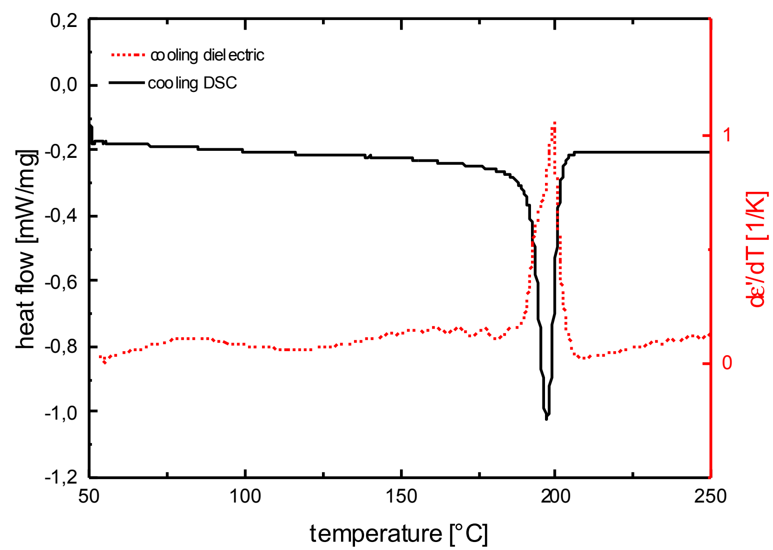
PA6, Ticona PA6-GF & Ticona PA6-CF



Correlation of DSC and DEA

Crystallization of Ticona PA6-CF60

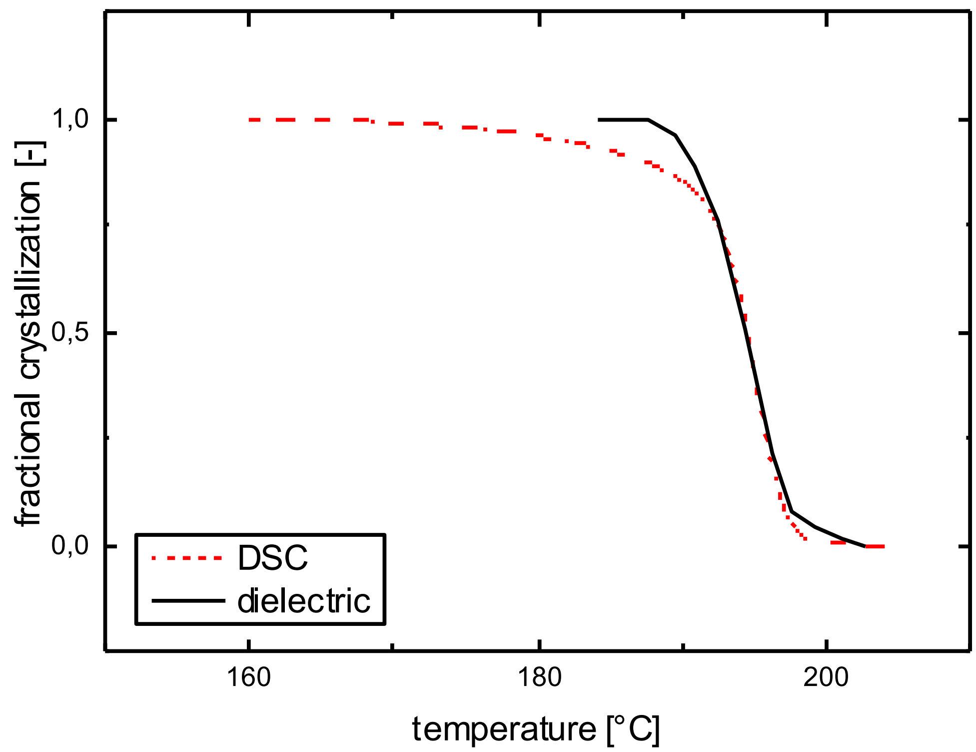




Chaloupka [5]

Correlation of DSC and DEA

Degree of Crystallization of Ticona PA6-CF60



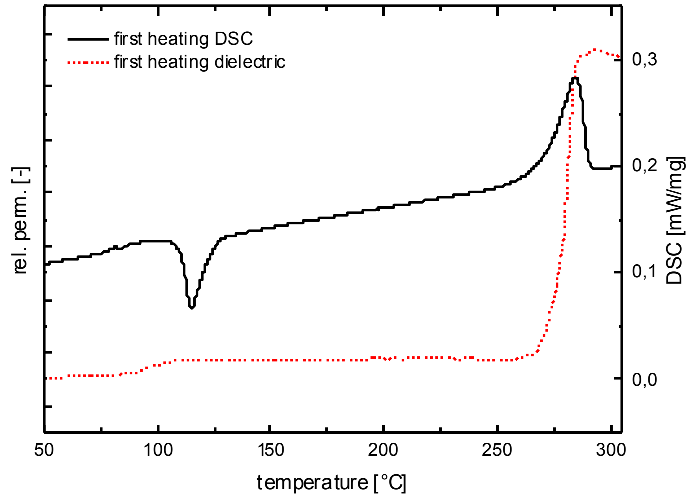
degree of crystallization is correlatable to DSC-results

Glass transition Tg, T_m and T_c

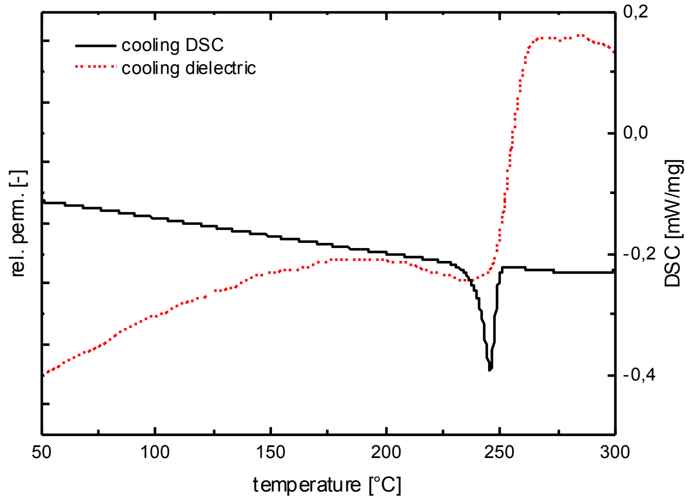
Ticona PPS-CF67

tool mountable (reusable) sensor

first heating



cooling



Glass transition		
	Onset [°C]	End [°C]
DSC	77,5	88,6
Dielectric	85,5	106,4
Melting T_m		
	Onset [°C]	End [°C]
DSC	269,5	290,1
Dielectric	276,2	284,2

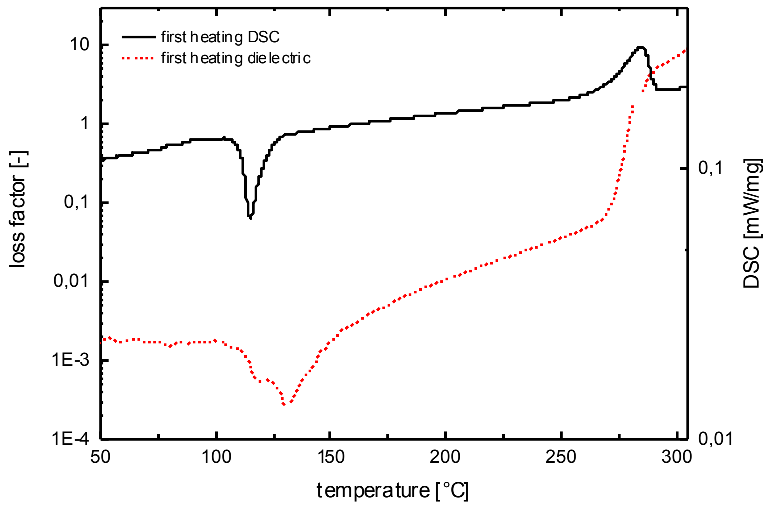
Crystallization T_c		
	Onset [°C]	End [°C]
DSC	239,4	249,4
Dielectric	246,8	260,8

Cold Crystallization

Ticona PPS-CF67

tool mountable (reusable) sensor

first heating



Cold crystallization		
	Onset [°C]	End [°C]
DSC	110,1	123,0
Dielectric	109,2	151,5
Melting		
	Onset [°C]	End [°C]
DSC	269,5	290,1
Dielectric	275,1	284,8

Conclusions

Summary

- Local melting and remelting of polymer material leads to more complex shrinkage and warpage cases
- Development of Young's modulus as a function of temperature and solidification is significant for part warpage
- Numerical simulation of warpage successful
- Error is decreased by taking inhomogeneity of the temperature field into account
- **All local deposition and melting processes are governed by these same phenomena.**
- **DEA** is suitable for online- measurements of phase transitions in composite manufacturing

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